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ABSTRACT

The thrust of this book is to indicate relative priorities of technology and the rationale for investment in United States space technology to meet future needs as assessed by the Committee on Advanced Space Technology. In part one, a discussion of potential mission sets is given, including: (1) "Mission Requirements for Space Transportation; (2) "Space Science and Applications: Technology Driver Missions"; (3) "Defense Space Research and Development Requirements and Technology Drivers"; and (4) "Humans in Space." In part two, recommendations are made regarding adequate programs in the technology areas of "Propulsion"; "Technology for Humans in Space"; "Life Support Systems"; "Automation, Robotics, and Autonomous Systems"; "Power"; "Materials and Structures"; "Information and Control Systems"; and "Sensors." In part three, rough priorities and estimated costs of each of the technology areas are discussed. Included is a bibliography and a list of participants. (ML)

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Space Technology to Meet Future Needs

Committee on Advanced Space Technology
Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

The National Commission on Space postulated an ambitious series of missions, culminating with a manned mission to Mars. While it is not clear which goals will be embraced by this and future administrations, whatever the choices, the nation should have the capability to execute the options chosen within predictable cost and schedule.

Key to that capability will be the research base that is available in the technologies critical to the chosen missions. Propulsion, power, materials, structures, life support, human factors, space medicine, automation and robotics, communication, instrumentation, guidance and control, and operations are the technology building blocks that enable missions.

The sources of the technology base in these disciplines should come, in large measure, from the advanced space research and technology (R&T) program of the Office of Aeronautics and Space Technology (OAST) within the National Aeronautics and Space Administration (NASA). Over the past 15 years, this program has been severely restricted and mainly focused on relatively modest advances in state-of-the-art support of near-term NASA missions. It is not an overstatement to say that NASA's preoccupation with short-term goals has left the agency with a technology base inadequate to support advanced space missions. For the past 15 years, less than 3 percent of the total NASA budget has been invested in space R&T. Of that, virtually none has been spent on technology development for missions more than five years in the future.

The Committee on Advanced Space Technology strongly believes that NASA must pursue a more balanced program with increased emphasis on critical long-term technologies. Investment today will not just enable a broad spectrum of possible future missions, but, if properly planned, will have important benefits to both the military and the civilian space industry.

We believe NASA's current Civil Space Technology Initiative is a promising start, but falls far short of what is eventually needed. There is no absolute formula for determining how much an organization should invest in new technology. In industry, management determines what is required to keep one's products competitive. Those who invest wisely prosper. Those who slight research and development in the interest of increasing profit become sunset industries.

NASA, as a high technology government agency charged by the Space Act with assuring the United States' leadership in space, faces an analogous set of decisions. How much R&T investment is required to keep the nation competitive?

For the past two decades, the percentage of the NASA budget invested in space R&T has been reduced in order to fund the demands of large operational programs such as the Space Shuttle. The result is that the agency is no longer a strong technical organization and the nation is fast losing its technical leadership in space.

To provide the basis for recommending a level of investment, the committee reviewed the state of advanced space R&T from the perspective of the needs of plausible future missions for space sciences, commercial applications, military needs, and manned exploration. The result was depressing.

Our national launch vehicle program is inadequate for its task. No new rocket engine development has been initiated for at least 17 years. The same can be said for orbital transfer vehicles where reusability and both high- and low-thrust engines with specific impulses much higher than the limits of conventional chemical thrusters can have great payoff in system design.

For many space missions, prime power requirements can exceed the 100 to 300 kW obtained from solar dynamic systems or conventional solar arrays. Heat rejection and efficient power distribution remain problems.

The dynamics of large flexible structures in zero gravity, vibration modes, damping, and control of critical dimensions under

thermal cycling are not yet well understood. Assembly of such structures on orbit has yet to be fully demonstrated.

New materials hold the promise of significantly reducing weight—the most critical parameter in sizing a mission. Materials science is also central to the development of nuclear power and advanced systems. Promising concepts must be reduced to practice and characterized for space.

Basic uncertainties exist with respect to man's ability to survive long duration space flight. Life support system technology has evolved very little since the initial Mercury designs. Each crew member uses some 10 lbs of consumables—oxygen, water, and food—per day. The potential benefits of a closed-loop life support system are enormous, but progress in the last 25 years has been desultory. The same can be said for spacesuits. The requirement for prebreathing and the inflexibility of the suit severely limit the effectiveness of the astronaut in extravehicular operations.

Up until now most operations in space have been performed manually, but the proper role for man in space is supervisory. Robots can relieve the requirements for extravehicular activity, with its attendant hazards, and perform functions that man cannot perform or reach places man cannot go. Robots for space differ from their terrestrial brethren. They must operate in zero gravity and they must be multipurpose and adaptable. Needless to say, advances in robotics will benefit both manned and unmanned missions.

Many space missions utilize the unique vantage point of space to look either outward through the solar system to the universe beyond or earthward to further understand our complex planet. The data gathered must be efficiently transmitted to Earth for analysis.

Sensors are key to observation, and much can be done to improve sensitivity and spectral range. We have yet to develop a long-life cryostat, essential to maximizing the performance of electro-optical sensors.

Information systems technology must be adapted to space needs. High-rate data transmission, efficient signal processing, and data compression and communication over long distances are but a few of the challenges. Attitude control and station keeping must become increasingly precise to improve the resolution of sensor systems.

To improve reliability and spacecraft life, system designs must

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be self monitoring and embrace fault-tolerant architectures. The need for support from Earth must be greatly reduced. In the survey of industry and universities conducted by the committee, the most important need identified was major reduction in the cost of putting a payload in its desired orbit. The effective use of automation, built-in testing, and a change in NASA's operational philosophy must all be advanced to the point where they can contribute to significant reductions in the number of people on the ground required to support a mission.

The litany is long and is detailed in the body of this report. It may not yet include all critical areas.

Before discussing budget levels, we note that in many of the technologies discussed above, programs that have addressed the issues were started in the 1960s and early 1970s and then terminated either because of budgetary pressure from the operational programs or because no programmed mission had been defined. While recognizing that sustained national commitment to challenging goals can "pull through" technology advances, at the same time technology programs must be judged on progress toward their goals, not solely on the basis of short-term contributions to nearby missions.

In this report, we do not wish to give NASA a detailed blueprint for its space R&T program. Rather, our thrust is to indicate relative priorities of technology and the rationale for investment. In Part II of this report we have made recommendations regarding adequate programs in some eight technology areas. In Part III we have placed rough priorities on the programs discussed and estimated the costs for an adequate program in each.

From analysis of that data, we conclude that the advanced space R&T program continues to be seriously underfunded—by at least a factor of three. The actual amount required for a vigorous and healthy R&D program is a function of how many demonstration programs (e.g., full-scale engine firings) are undertaken. We believe that if a reasonable investment in R&T is made, the nation will have the technological options ready when needed.

Joseph F. Shea
Chairman, Committee on
Advanced Space Technology

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Introduction and Summary Recommendations

In the 1958 Space Act[1] establishing the National Aeronautics and Space Administration (NASA), Congress "declares that the general welfare and security of the United States requires that adequate provision be made for aeronautical and space activities." These activities "shall be conducted so as to contribute materially to . . . preservation of the role of the United States as a leader in aeronautical and space science and technology and in the application thereof to the conduct of peaceful activities within and outside the atmosphere."

For two decades, NASA has focused its attention on major operational missions, such as Apollo, Skylab, Viking, and the Shuttle, to support other objectives in the Act that require activities to expand human knowledge, improve aeronautical and space vehicles, develop vehicles capable of carrying equipment and living organisms through space, and cooperate with other nations in "work done under the Act and in the peaceful application of the results of that work." Since the Apollo program, little has been done to enhance or develop the basic technologies that will enable future missions or provide the nation with a variety of options for the space program. The Shuttle itself was built largely with off-the-shelf technology.

Early in the 1980s, the Aeronautics and Space Engineering Board (ASEB) of the National Research Council recognized serious

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problems in the nation's space technology program. The emphasis on large operational programs without a concurrent investment in basic technology had seriously eroded NASA's ability to undertake advanced missions. The United States was "eating its seed corn" to finance the Shuttle and was not developing the technology base required for the missions of the next century. For the past 20 years, space technology activity has been characterized by projects begun and abandoned; for example, the nuclear electric and nuclear rocket propulsion programs which ended in 1973.

In 1982, the ASEB conducted a workshop and produced a report[2] that found, among other things, that the high cost of space systems and transportation to space was inhibiting the civil and commercial use of space. The report recommended that the highest priority be given to technologies "that promise to reduce the cost of spacecraft systems, payloads, transportation, and operation." Further analysis led to the conclusion that NASA should play a role in space technology analogous to its historic role in technology development for aeronautics.

In the four years since that workshop, several things have happened to exacerbate the problem of space technology: NASA focused its attention on another major operational mission, the Space Station. The embryonic space processing industry virtually collapsed because of the high cost of space systems and the lack of cheap, assured access to space. Other nations challenged U.S. leadership in science and technology. One activity, the National Commission on Space (NCOS) in its report, *Pioneering the Space Frontier*, fully addressed the problem and recommended a substantial increase in the space technology program. But this report has not been formally accepted by the Administration as a basis for policy decisions.

Recognizing the need to revisit the conclusions of the first study and seeking guidance should the nation even partially adopt the recommendations of the NCOS, NASA requested the present study in late 1985. Just as the study was getting under way, the Challenger tragedy occurred. The attendant two year's hiatus in space missions clearly demonstrates the validity of the early concerns about the state of space technology. With the Shuttle grounded, the nation has no alternative system to launch the large spacecraft vital to

the security of the nation and is in the process of reviving expensive expendable launch vehicles based on technology from earlier decades.

In keeping with the obligations of the Space Act, the ASEB considers NASA's mission to be broader than operating a transportation and data collection system and developing technology to support NASA programs. NASA has the responsibility to regain the nation's leadership in space technology. It must provide technology to support space science missions aimed at increasing knowledge, apply the technology to help meet the needs of mankind, and provide options and alternative approaches for future civil and national security missions.

The NASA advanced space technology program is the responsibility of the Office of Aeronautics and Space Technology (OAST) and at present is conducted primarily in-house at the NASA research and space flight centers, but with some support by work conducted under contract with industry and universities. Additional technology development is sponsored by several NASA program offices: the Office of Space Flight (OSF), the Office of Space Science and Applications (OSSA), the Office of Space Tracking and Data Acquisition (OSTDA), and the Office of Space Station (OSS). Each of these NASA program offices except OAST is oriented toward either mission or operations responsibilities, and the space technology sponsored by the mission offices is focused on satisfying these responsibilities. Thus, the space technology sponsored by these groups tends to be relatively near-term and focused on specific systems. In addition, conservative design and planning often militates against development of new approaches.

On the other hand, the space research and technology development (R&T) programs sponsored by OAST are intended to ensure technology readiness for future needs. The 1982 ASEB workshop explored whether the OAST space R&T program should endeavor to meet the needs of civil, commercial, and military space systems in a manner analogous to NASA's traditional role in providing a technology base for the aeronautics industry. The workshop concluded it was indeed the proper role for NASA, again in accordance with the Space Act. NASA accepted the recommendation and has restructured the space R&T program to some extent. However, the current R&T program does not yet provide the technology advances and new technologies needed by the nation's space industry, the U.S.

Department of Defense (DOD), and space scientists. The ASEB has become increasingly concerned over the paucity of resources being applied to long-range technology research and development (R&D).

To better assess the situation, during the winter of 1985-1986, Dr. Raymond Colladay, NASA associate administrator for aeronautics and space technology, requested that the ASEB undertake an independent evaluation of national advanced space technology requirements for the next 30 years. The study was to take into consideration both mission goals and the need for reduced transportation and operations costs, and recommend a technology development program for an aggressive civil future in space.

Specifically, the ASEB was requested to form an ad hoc study committee to:

- Agree upon a challenging set of missions for the next 30 years, including requirements for low-cost transportation and operations in space.
- Recommend a long-t m technology program focus, identify priority enabling and enhancing technologies, and broadly estimate requirements for manpower, facilities, and other resources.
- Identify areas where new, innovative approaches are likely to produce exceptional systems benefits.
- Consider what the balance should be between development-of-understanding level and demonstration projects to assure the use of new technology.
- Recommend potential areas for greater university and industry involvement in the creation and direction of the OAST space R&T programs.

The results of the study appear in this report.

APPROACH

In January 1986, four members of the ASEB (Drs. Richard Hesselbacher, Peter Likins, James Kramer, and Joseph Shea) met in Washington to explore alternate approaches to the requested task and to suggest areas of expertise that would be needed on the study committee. They determined that prior to defining technology needs, likely sets of challenging missions through 2015 A.D. should be identified in the following categories: space transportation, space science, defense R&T needs, and humans in space. The

group believed missions designed for man's exploration of the universe belonged to a distinctive category apart from the other three. Lower transportation costs were regarded as the key to commercial activities in space.

From the four mission sets, the enabling technology development and timing for technology readiness would be determined. In addition, the group noted an important caveat: a national technology base should not be solely mission-oriented, but should consist of research to better understand physical phenomena and to build a technology base that could be utilized by the civil, government, commercial, science, and defense sectors.

The ad hoc study committee was formed and met on June 5-6, July 14-15, November 12-14, 1986, and during the week of February 2-6, 1987. At its initial meeting, the committee heard from the directors or representatives of a number of contemporary studies in this area including Dr. Thomas Paine, chairman of the NCOS, and Dr. Thomas Donahue, chairman of the National Research Council Space Science Board's study on Space Science in the Twenty First Century (see Appendix B for a full list of participants). The second meeting consisted largely of an in-depth exploration of NASA's research and technology programs, in both the OSSA and OAST, along with committee deliberations over technologically challenging mission sets.

At the third meeting, outstanding technology briefings on humans in space, automation and robotics, materials for the space and entry environment, space structures, propulsion, and power were presented by invited speakers. The group held discussions with Dr. Sally Ride regarding strategic planning,* with Dr. Leonard Harris on the OAST Civil Space Technology Initiative and possible follow-up programs, and with NASA Ames Research Center Director Dr. William Ballhaus, Jr. Representatives from all of the NASA centers and from headquarters were in attendance and exchanged views with committee members.

Through a survey of aerospace industry leaders (Appendix C) and of universities with active aerospace departments (Appendix D), the committee sought to augment its own views and expertise regarding (1) the greatest needs for technology development, (2) opportunities for technology advances, and (3) the most appropriate

* Before publication of the Ride Report in August of 1987.

and effective role for NASA. An almost universal response confirmed the need for less expensive and more reliable transportation to orbit, and authoritative positions were taken advocating many other areas that were subsequently considered in developing the committee recommendations. Many responses also indicated a keen interest in having NASA provide unique facilities for in-space R&T.

When the committee held its workshop in February 1987, the inputs from these various sources were considered in arriving at findings and recommendations regarding a long-term program for technology development. The committee selected eight areas of space technology as requiring emphasis in coming years and treats these areas in detail in this report. Estimates were then made of the level of effort required for the nation to have meaningful programs in these areas. Last, an economic perspective of the space industry was prepared by committee member Wolfgang Demisch and is printed in full as Appendix A. Workshop results were subsequently reviewed by the ASEB.

Recommendations in the report are intended to pertain to the entire NASA effort and are not limited to the Office of Aeronautics and Space Technology. The committee allotted considerable time to studying future space science missions because of the varying nature of these missions and their technological demands. Throughout the report, it is assumed that the Space Station will come into existence in the 1990s and that R&D on the National Aerospace Plane will continue; these programs, therefore, are not studied in depth in the following pages. It is clear that any near-term advances in the technology areas recommended for emphasis in this report could be of value to these programs.

Members of the committee wish to express their gratitude to the chairmen and representatives from other studies who took time to discuss their reports with the committee; to the very stimulating speakers who presented discussions of technical issues; to the individuals who served as liaison representatives from NASA and other organizations; to representatives from industry and universities who gave the committee the benefit of their views in their thoughtful responses to the surveys; and to the Research Council staff for its conscientious and professional support at every phase of the study.

SUMMARY RECOMMENDATIONS

The committee selected representative categories of future space missions and determined the technologies needed to enable those missions. It recommends that emphasis be placed on the following disciplines, in the order in which they appear. These are areas, relatively neglected during the past decade or more, where advances may enable new capabilities.

1. ***Advanced propulsion*** should be afforded the highest priority and the committee recommends that engine design and development activities should be pursued in the following areas:

- a range of advanced Earth-to-orbit engines,
- reusable cryogenic orbital transfer vehicles,
- high-performance orbital transfer propulsion systems for such tasks as sending humans to Mars, and
- new spacecraft propulsion systems for solar system exploration.

2. An examination of technologies to enable ***humans in space*** to live and work productively, including ***life support systems***, quickly revealed that little is understood about the long-term effects of microgravity on the cardiovascular and musculoskeletal systems. The committee recommends closely monitored, systematic low-gravity exposure of humans, with incremental increases in duration, as well as long-duration animal experiments to assess deconditioning and to determine the effectiveness of countermeasures. Only after the results of such tests are assessed can a determination be made regarding the need for artificial gravity for manned missions of more than a year's duration. In addition to research on the effects of low or zero gravity, accelerated research is recommended on the following:

- radiation protection,
- closed-cycle life support systems,
- improved equipment for extravehicular activities,
- augmentation of human capabilities with autonomous systems and robotics, and
- human factors, including crew selection and training, psychological stress, and man/computer interfaces.

3. *Autonomous systems and robotics* can augment human capabilities and enable dangerous or long-duration missions, both manned and unmanned. Emphasis should be placed on these areas:

- lightweight, limber manipulators,
- advanced sensing and control techniques,
- teleoperators, and
- artificial intelligence and advanced information processing including "trainable" systems.

4. *Space power supplies* of the future should include photovoltaic, solar dynamic, and nuclear sources. Only reactor-generated power can meet anticipated high-power requirements, and NASA should increase its involvement in the SP-100 program, an interagency nuclear space power (SP) research and demonstration program designed to achieve 100 kW of space-based power.

5. In the area of *materials and structures*, advanced metallic materials offer the greatest potential, through alloy synthesis, for dramatically reducing weight and increasing payload to orbit. "Hot" structures can counter reentry heating in a cost-effective manner. The committee recommends greater emphasis on understanding basic processes and characterizing new materials for the space environment. The NASA program is relatively small in relation to the national effort and NASA must avail itself of developments in industry, universities, and the DOD while concentrating on space-unique requirements such as reentry and extreme temperature changes.

In dealing with the dynamics and control of large, flexible space structures, mathematical models of the precision required are not yet developed, and emphasis should be placed on systems that can "learn" after the spacecraft is in orbit and alter control systems automatically.

6. NASA's *information and control systems* program should also utilize technology available from industry, universities, and the DOD and should focus on:

- autonomous computing systems designed for the space environment and enhanced on-board capabilities,
- high-speed, low-error rate digital transmission over long distances,

- voice and/or video communications for continuous real-time communication,
- space-borne tracking and data relay capabilities,
- enhanced on-board computing capabilities,
- instrumentation to monitor equipment condition and to avoid hazards, and
- ground data handling, storage, distribution, and analyses.

7. Advanced *sensor technology* is essential to leadership in space science and applications. The committee recommends emphasis on four principal and two supporting areas:

- large aperture optical and quasi-optical systems,
- detection devices and systems,
- cryogenic systems, and
- in-situ analysis and sample return systems.

The recommended supporting areas are (1) radiation insensitive, on-board computational systems and (2) high-precision attitude sensors and axis transfer systems.

In examining the history of space technology research and development, the committee noted many instances of programs that were started only to be terminated before technology was ready for application. For the last 15 years, NASA's investment in basic research and technology development has been lower than the sustaining level required by most industries. The results are that the United States is losing its competitive lead in space, and new technology is unavailable to offer the nation a selection of future options in space.

Based on its deliberations regarding a space program adequate to meet national needs, the committee recommends that an assured level of no less than 7 percent of the NASA budget be permanently allocated to research and technology development. The breadth of opportunity available argues for an investment as large as 10 percent.

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Part I:
Potential Mission Sets

1
Mission Requirements for Space Transportation

Space activities should be more than a discretionary element of U.S. government and private efforts: a sustained effort is essential to national defense and economic well being. Communications, navigation, and Earth observations (meteorological, oceanic, and land) are supported operationally by space systems of the public and private sectors.

The nation requires spacecraft launch and interorbital transfer capabilities that are commensurate with increasing mission requirements as well as reliable and affordable. These are minimum requirements to meet the needs of current space activities. Whether the requirements are satisfied by civil, governmental, defense, or private efforts is a matter of public policy and economics.

Fostering innovative new private and public activities in space, beyond those of the present, requires advances in either the technology or economics of launch and orbital transfer. The threshold to entry, whether technical or cost, must be lowered to permit new activities to be either feasible or cost effective.

Two categories of activities can be the focus of the nation's efforts in spacecraft launch and interorbital transfer. The first is one of incremental improvements and technological or economic consolidation. The second is that of breakthrough technology directed

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at reaching a new plateau of capability. Neither category necessarily takes precedence; both are difficult, highly challenging efforts that must be carried out to sustain the health of the nation's space program. They simply have a different focus. Both involve basic research and can be legitimate functions of government.

NASA'S ROLE

It is the responsibility of the National Aeronautics and Space Administration to ensure that the critical technologies for space vehicles are continuously advanced in level of understanding so that they can be employed with acceptable risk in the design and development of:

- new generations of vehicles to perform currently feasible missions with higher reliability and lower cost, and
- systems that enable new mission capabilities.

In pursuit of these objectives, two somewhat different types of research and technology development should be carried out within the NASA research centers and their contractual affiliates in industry and universities. One area of R&T focuses on increasing the understanding of phenomena critical to the performance or durability of systems of relatively conventional concept or design. Examples of such work would be studies of the phenomena that limit the life and performance of bearings and seals for high-performance turbopumps, studies of the heat transfer and thermal stress phenomena in very high pressure hydrogen-fueled engines, design and development of fault tolerant, highly reliable propulsion control systems, and development of structures that are lighter and more reliable than those presently available.

The other area is to conceive and study new concepts that will enable new missions not possible or practical within the existing conceptual framework of space transportation. Recent examples of such conceptual advances are the tether* and the solar sail. Other examples older in conception but still young in terms of feasibility demonstration are nuclear-electric propulsion and space-based reusable orbital transfer vehicles.

*Tethers refer to a constellation of two or more bodies in space connected by a string, rope, or wire. Such systems have unique behavioral characteristics and applications of interest include momentum transfer, a space "elevator," and upper atmospheric research.

It is primarily research analogous to the second category that NASA has conducted for many years in support of the commercial and military aeronautical industry. In aeronautics, these NASA activities have been severely scrutinized over the last few years and strongly endorsed in every study undertaken.

FUTURE TRANSPORTATION NEEDS

The United States is now firmly committed to the need for a diverse, flexible family of Earth-to-orbit launch vehicles, capable of both one-way transport of satellites and other cargo as well as safe two-way transport of humans and high-value payloads that must be recovered from space. There is a need for modern technology in future vehicles of all classes to enable new capabilities such as heavier lift capacity, to improve reliability, and to lower cost.

The trend toward ever larger payloads shows no sign of abating. Whether for carrying large cargo elements to a space station or launching communications satellites, increasingly sophisticated uses lead directly to greater launch requirements. In the case of communications, 10,000 lb satellites are likely to be commonplace in the late 1990s, with some moving toward 15,000 lbs and higher. This trend is fostered by the continuing move to multiband, multipurpose satellites both domestically and internationally. The combination of C- and Ku-band fixed satellite services is one example, while the combination of radio determination satellite services at L-band with fixed satellite services is still another.

A reasonably accurate rule of thumb places the weight of the orbital transfer stage at five to six times the geostationary payload. Thus, as spacecraft pass the 10,000 lb mark, the cargo to be launched passes 50,000 to 60,000 lbs. If the launch costs are to be shared with a second, smaller spacecraft, the total lift capability should exceed approximately 100,000 lbs. Even higher lift capabilities would obviously be required if both spacecraft were of the 10,000 lb or greater class.

Thus, a launch vehicle with a lift capability of more than 100,000-150,000 lbs to low Earth parking orbit is a fully supportable national objective. This is consistent with the American Institute of Aeronautics and Astronautics' report describing a future series of Shuttle-derived vehicles beginning with a 150,000 lb class and progressing through several stages to 400,000 lbs.[1] The need for such

a vehicle has also been recognized recently by the U.S. Department of Defense. The Soviet Energia launches 222,000 lbs into low Earth orbit (LEO).

Similarly, while it is feasible to construct the current design for the Space Station using the Space Shuttle, a heavy lift vehicle offers advantages for Space Station assembly, and future cargo operations are likely to require greater capabilities. Economical and routine use of the Space Station is likely to militate toward a more efficient launch system as well. The later evolution of the Space Station and deployment of its related astronaut-tended platforms will also require a flexible, high-capacity launch vehicle. The Polar Platform, for example, will be installed in a sun-synchronous, near-polar orbit at an altitude of approximately 800 km. The platform is expected to weigh well in excess of 30,000 lbs and require biannual servicing. At a minimum, the installation of the platform on orbit would require two Shuttle launches or one or more unmanned launches.

The above requirements are consistent with the discussions accompanying the Joint DOD/NASA National Space Transportation and Support Study, and appear to provide suitable objectives for the national research program in this area. While some requirements could be met using expendable launch vehicles, as is expected in the recently announced defense initiative, it appears that unmanned reusable vehicles offer great potential for major advances in launch capabilities.

Therefore, one worthy objective would be the development of the enabling technology for a reusable vehicle in the class greater than 100,000-150,000 lbs to LEO.

A second important objective is to put in place the technology base for a new generation of small and medium launch vehicles. Here the emphasis should be on technological advances that will enhance reliability and lower manufacturing and operating costs, as well on the more usual measures of performance such as higher engine thrust-to-weight ratios, higher specific impulse (Isp), and lower structural weight fractions. Whether this new class of vehicles should be reusable is not clear at this time.

The need for OTVs has been alluded to above; many NASA, civil, and defense missions have requirements that greatly surpass current capabilities. The Polar Platform, for example, would benefit from a reusable stage that could be refueled in orbit and that would

provide the energy increment to raise and lower the platform between a servicing altitude of nominally 400 km and the operational altitude of 800 km. In other scientific and applications missions, the need exists to change the orbital plane of the mission to observe targets of opportunity or to optimise the scientific return. Current technology permits only the brute force technique of carrying larger and larger fuel tanks; advanced technologies should permit more efficient solutions.

The technologies for the transatmospheric Aerospace Plane are under development by an interagency program in which the Office of Aeronautics and Space Technology participates. On the assumption that it will continue, the Aerospace Plane and its missions will not be discussed further here. It should be noted, however, that the technologies of the advanced Shuttle craft and the Aerospace Plane are highly synergistic, e.g., guidance, control, thermal control, and structures.

TRANSPORTATION FOR FUTURE SPACE SCIENCE MISSIONS

Planetary exploration missions have frequently employed high-energy launch capability. The Titan III-Centaur combination, for example, was employed for Viking and Voyager. The Galileo mission was originally planned to use the Shuttle-Centaur combination. The cancellation of that combination in the aftermath of the Challenger disaster has left the fate of the Galileo mission in doubt and has placed a number of other desired science missions outside the performance envelope of available launch vehicles and stages. These capabilities will be replaced in the near term by use of the Titan-IV and smaller vehicles.

In the long term, the aspirations of the science community and the objectives such as those stated by the NCOS will necessitate even greater capabilities at lower cost. Both the Mars transfer vehicle and the so-called "cycling spaceships" represent missions requiring technologies not currently in hand. Raising the space science and exploration capability to its next plateau requires that they be addressed.

TRANSPORTATION MISSION SET—2015

The following set of missions presents technological challenges that must be addressed to meet national space transportation needs:

- Modern expendable launch systems of small and medium capacity
  - — Payload weight: 20,000 to 50,000 lbs to LEO
  - — Reliable
  - — Low operational cost
  - — Improved payload-to-lift mass
- Unmanned heavy-lift launch capability to LEO
  - — Payload weight: greater than 100,000 lbs
  - — Payload envelope: as unrestricted as feasible
  - — Cost: substantial reduction over current systems (full or partial reusability will be determined by economic trade-off)
- Reusable orbital transfer system to raise payloads from LEO to higher altitude sun-synchronous or geostationary orbit and return them
  - — Geostationary payload weight: greater than 20,000 lbs
  - — Payload envelope: as unrestricted as feasible
  - — Robotics: capable of interfacing with an intelligent front-end for routine servicing operations
- Advanced space transportation system to replace the Space Shuttle after the turn of the century
  - — LEO payload weight: 20,000 to potentially greater than 100,000 lbs
  - — Payload envelope: as unrestricted as feasible
  - — Automation and robotics: used to reduce turn around time and mission costs, with special emphasis on self-diagnostics
  - — Trade-off will be made between Shuttle II and the trans-atmospheric Aerospace Plane
- High-energy interplanetary transfer system to meet objectives of the NCOS
  - — High Isp, high-thrust, long-life propulsion systems to minimize trip duration to Mars (e.g., 10,000 lbs or greater thrust, 800 sec Isp)
  - — High Isp, long-life propulsion systems to enable outer

planetary scientific missions (e.g., very low thrust, greater than 1,000 sec Isp)
- Nuclear-electric or direct-thrust engines are candidates for these missions
- Hybrid power and propulsion systems are another attractive option

The National Aerospace Plane effort has been defined by an interagency body with dominant input from the DOD and, as noted earlier, is not treated fully in this report. Close coordination between DOD and OAST in this effort and the other space transportation development activities mentioned above is essential.

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2
Space Science and Applications: Technology Driver Missions

BACKGROUND

The National Research Council's Space Science Board believes "that scientific objectives can provide any desired degree of challenge in the development of space technology."[1] The technical requirements of scientific missions under development and in planning for the next three decades certainly challenge all phases of technology, particularly if a requirement for human presence in the exploration of the planets is included.

Experience shows, however, that a nation should not rely entirely on the known requirements of science to drive its total advanced technology program or even to provide the technology for its future scientific program. Science and technology proceed hand in hand through the ages with first one and then the other leading. Scientific understanding enables new technology and new technology enables new areas of scientific research. Scientific research into the nature of electricity produced the knowledge that enabled the creation of the electrical industry. The existence of an electrical industry enabled the creation of the particle accelerators required to understand nuclear interactions. The development of transistor technology enabled the miniaturization of instruments required for

a successful space science program. NASA's space technology program not only must provide for the known requirements of science but also an opportunity for creative people to develop new technologies that can enable presently unforeseen scientific experiments.

A plethora of resource material is available to describe potential technology driver missions.[2,3,4,5,6] Materials from reports prepared by the Advisory Committees of NASA, the National Research Council, and the NASA Long-Range Program Plan were used to develop mission requirements and the NASA Space Systems Technology Model[7] was used to understand the status of the technology development under way as well as OAST's plans for future development.

Technology driver missions were derived by first reviewing the missions under development by the Office of Space Science and Applications (OSSA) to understand the state of the art in space science technology. Next to be developed was an "Early Mission Set," a set of three missions that require technology to be ready by the mid-1990s and which, when taken together, establish an envelope of requirements encompassing all of the space science missions for this period. The committee then considered the missions proposed for flight in the early decades of the twenty-first century and analyzed the long-range trends in particular technologies that seemed to be most critical to space science or most challenging to technology development. Finally, the committee developed a "Later Mission Set," a set of six missions that, while only concepts at this time and not requiring technology until the early part of the next century, can serve as driver missions establishing the long-range trends in scientific requirements.

CURRENT STATUS OF CIVIL SPACE TECHNOLOGY

Figure 1 shows the major OSSA missions and their schedules and provides a rough indication of the current status of space science technology. In astronomy, the Hubble Space Telescope (HST) and the Gamma Ray Observatory (GRO) are the only missions firmly scheduled as of July 1987. The HST, with its requirement for 2.4 m diameter, diffraction-limited optics, 0.1 arc sec resolution, and on-orbit refurbishment has provided the major challenge for spacecraft and instrument technology for the past decade, particularly for technology supporting optical observations in the visible portion

of the spectrum. A successful launch and operation of the HST in 1988 will demonstrate the availability of this level of space astronomy technology. The highly successful Infrared Astronomy Satellite (IRAS) required the development of, and demonstrated the availability of, technology for cryogenically cooled optics, but not the technology for maintaining a permanent cryogenically cooled observatory in space. The EINSTEIN X-Ray Observatory hardware establishes the current status of x-ray astronomy technology.

In planetary exploration, Galileo, with its requirement for a capsule to enter and measure the properties of the outer portion of Jovian atmosphere, has provided the major challenge for planetary exploration technology for the past decade. The Viking mission demonstrated the availability of the technology to land and survive on the surface of Mars but not the technology to rove or collect and return samples. The USSR's VENERA missions demonstrated the availability of Soviet space technology to land and survive briefly on Venus but obviously not to rove or return samples.

The Upper Atmosphere Research Satellite (UARS) and the Ocean Topography Experiment (TOPEX) have driven the technology of Earth-observing instruments for the past decade but have not seriously challenged spacecraft technology. The Magellan Venus radar mapper and the Shuttle's imaging radar have developed synthetic aperture radar (SAR) technology, including specialized onboard data processing techniques.

Although not shown in Figure 1, and yet to be approved for development, two astronomy observatories, the Advanced X-ray Astrophysics Facility (AXAF) and the Space Infrared Telescope Facility (SIRTF) are planned. NASA has Phase B studies under way on both of these missions and new starts are planned for both as soon as the funding for space astronomy permits. These two permanent astronomical observatories, together with the HST and GRO, make up the four permanent observing facilities that the United States plans to have in operation by the beginning of the next century. AXAF is the driver mission for x-ray optics and instrumentation. SIRTF requires the technology for infrared detectors and imaging systems and the tools and technologies required for operating and resupplying cryogenically cooled optics in space.

Together, the HST, AXAF, and SIRTF illustrate the status of the basic technology supporting astronomical observations from space for the three most challenging regions of the electromagnetic

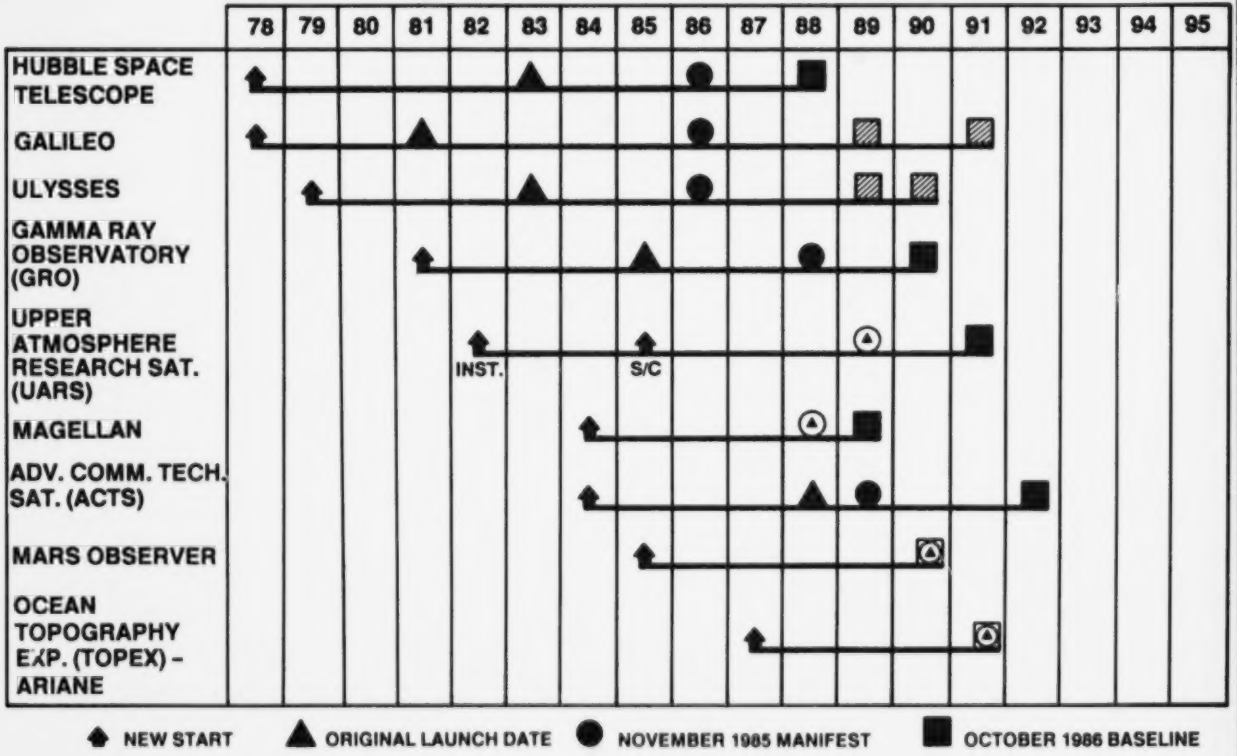

FIGURE 1 Major flight missions planned by the NASA Office of Space Science and Applications.

TABLE 1 Current Status of Key Elements of Space Science Instrument and Spacecraft Technology, Circa 1990-1995

Astronomy
Permanent human-tended astronomical observatories in space with on-orbit refurbishment of spacecraft systems, including cryogens, and exchange of experiments. Experiments will include cryogenically cooled optics and detectors.
At 0.5 micrometers (HST):
2.4 m diameter, diffraction-limited optics
0.1 arc sec angular resolution
4.5 m^2 collecting area
At 1 nanometer (AXAF):
1.2 m diameter grasing incidence optics
0.5 arc sec angular resolution
1.0 m^2 collecting area
At 4 micrometers (SIRTF):
0.9 m diameter diffraction-limited optics
1 arc sec angular resolution
0.5 m^2 collecting area
Planetary Exploration
Viking:
1,000 kg, 1-year lifetime landers on Mars
Galileo:
Atmospheric entry and measurement for Venus, Mars, Jupiter, Saturn, and Titan
Navigation ability to orbit Jupiter and fly by each of its moons
Earth Observation
UARS and TOPEX:
5,000 kg payloads to 850 km sun-synchronous orbit
10 m surface resolution
1 kW average power
100 Mb data handling capability

spectrum—infrared, optical, and x-ray. Table 1 summarizes the status of the basic technology for these three regions of the spectrum. The other major region of astronomy, gamma ray astronomy, is not a major driver of structural or guidance and control technology.

The development of the technology required for the Gravity Probe-B mission has been under way since 1962. This is an example of the long lead times frequently required for technology

development. This mission requires the measurement of the precession of the spin axis, relative to the fixed stars, of a cryogenically cooled gyroscope to an accuracy of about 0.001 arc sec. The actual precession is expected to be about 0.044 arc sec per year. This mission has been a major driver of instrument and spacecraft technology for 25 years. It has been approved for a test flight on the Shuttle sometime in the early 1990s.

Gravity Probe-B is a crucial mission for space technology. A successful test flight would demonstrate a substantial advance in space technology, and the detection of the predicted gravitational effects would substantially increase the requirements for the technology to support the extremely precise control and measurement of the orientation and location of spacecraft. Some general relativity experiments under consideration will require control and measurement of the orientation of a spacecraft in the microarcsecond range and the relative location of spacecraft to about one part in 10^{15}.

There are two areas of space science, microgravity and bioscience, where it is difficult to define the status of the technology or driver missions for future technology. The Space Science Board's study[1] concluded that microgravity research was in its infancy and that its prospects for the twenty-first century could not be evaluated until the results of preliminary experiments are available. As a result, the board did not develop a program for microgravity science. It recommended instead that technology be developed to obtain the lowest possible gravity conditions and sensors to characterize precisely the gravity levels and the vibration spectra during microgravity experiments. There is, however, a limit to the level to which the gravitational forces can be reduced due to the natural gradient in the Earth's field with altitude. This gradient produces a small (10^{-6} to 10^{-8}g) variation in the gravitational field over the experimental apparatus depending upon the size of the apparatus. Lower levels can only be reached by reducing the size of the apparatus or operating the spacecraft at a higher altitude.

Bioscience is concerned with the relation between living systems and the Earth and the effect of microgravity on living systems. The Earth Observing System (EOS) drives the technology for the systems required to study the relation between biota and the Earth. Space biologists plan to study the processes of all reproduction, growth, and modifications of living systems in the microgravity

and space radiation environment. Technology is required to conduct biochemical and biophysical studies of living organisms in an environment where the gravity can be controlled between 1 and 10^{-6} g. Bioscientists require advances in artificial intelligence (AI) and automation technology to help maintain and study laboratory animals in a microgravity environment. In addition, sophisticated, conventional instruments currently in use in ground-based research must be modified for use in space laboratories.

Driver missions for humans in space are covered elsewhere in this report. The requirement of these life science missions will also drive the technology required for microgravity and biological research in space. The laboratory facilities planned for the Space Station best illustrate the status of the technology to support microgravity and biological research to be expected by the mid- to late-1990s.

Table 1 summarizes the expected status of space science technology in the late 1980s to early 1990s. In looking at the long term, space scientists' requirements for the mid- to late-1990s need to be considered. Astronomers will want improved angular and spectral resolution and larger collecting areas. Planetary exploration scientists will want to land, rove, explore intelligently, and return well-selected samples from Mars, Venus, comets, the asteroids, and moons of other planets. Earth scientists will want to observe continuously the entire Earth for at least a 22-year period (one complete solar cycle) at all available wavelengths at the highest achievable resolution obtainable. The committee selected three missions, one each for astronomy, planetary exploration, and Earth observations, as technology driver missions for technology to be available in the mid-1990s.

TECHNOLOGY DRIVER MISSIONS FOR SPACE SCIENCE FOR THE MID-1990s

The committee attempted to identify a single "technology driver" space science mission, a mission whose technical requirements would challenge all areas of technology required for space science for the next decade, but rapidly concluded that such a mission did not exist. Astronomy missions will push the optical, large structural, and guidance and control technology but will not push

the technology required for planetary exploration. A planetary mission that requires improved capabilities in planetary landers, rovers, and sample return does not push optical or structural technology. Therefore, as noted above, the committee selected three missions, one in each of the three major disciplines of space science: astronomy, planetary exploration, and earth science. The committee selected missions that required a substantial advance in technology beyond that in Table 1 and that it believed would ultimately be undertaken. They are scientifically desirable, technically feasible, and within nominal budgets of the Office of Space Science and Applications. For earth sciences the committee selected the Earth Observing System (EOS) mission, for astronomy the Large Deployable Reflector (LDR), and for planetary exploration the Mars Sample Return (MSR) mission.

Earth Observing System (1990s)

NASA has conducted several studies of EOS.[8] EOS consists of a group of instruments placed in a sun-synchronous near-polar orbit (850 km) to study the Earth's atmosphere, surface, and interior (Figure 2). Current scientific plans require three EOS platforms. The EOS platforms are planned to be the Polar Platforms of the Space Station program. These platforms would be designed to be launched and serviced from the Western Test Range by the Shuttle. Instruments would be refurbished and replaced in orbit. The instruments are grouped into three packages, a surface imaging and sounding package (SISP), active microwave sensors (SAM), and instruments to monitor the physical and chemical properties of the atmosphere. The National Oceanic and Atmospheric Administration (NOAA) is expected to use these same platforms for operational, meteorological, and remote sensing systems.

The EOS payload will weigh 5,000 kg, and will require 10 kW average and 13 kW peak power as well as the capability to record onboard and transmit a 300 megabyte per second (MB/sec) data stream. Platforms are required to operate for 20 years with on-orbit servicing. Whether servicing will be at the platform's 850 km operational altitude or at the 280 km Shuttle altitude is an open question. However, it is likely that cost and Shuttle payload constraints will require automated and/or robotic servicing at the operational altitude of the platform.

FIGURE 2 Artist's concept of Earth Observing System polar orbiting mission. *Courtesy of NASA.*

The EOS requirement for precise, coordinated pointing of several instruments provides a major technological challenge. The weight and number of instruments is roughly an order of magnitude greater than the current missions, such as UARS and TOPEX. The sheer size and weight of the payload and the platform is a formidable problem. In principle the pointing and stability problem can be solved by the individual instruments through image motion compensation, or by use of a "smart structure" to control the entire platform or by ground processing of the data to eliminate image motion. The exact mode is yet to be chosen. It will result from a trade-off between the flexibility and the attendant cost and complexity of a multitude of individual solutions, and the potentially cheaper and more capable but less flexible system that relies on the ability to point and stabilize the entire system to the required accuracy.

EOS instruments require more reliable and more efficient laser systems. The requirements of the Lidar Atmospheric Sounder and Altimeter provide the greatest challenge to laser technology. Lasers are required with a 10-year, 10^9 shot lifetime and a 2.5 kW power supply. Location of the platform must be known to 1 m in the vertical and 10 m in the horizontal direction.

The EOS electronically steered radiometer presents a major challenge to attitude and structural control. The antenna is 18 m × 18 m. Distortions due to differential thermal heating will require real-time attitude determination of different parts of the antenna structure.

The high-resolution imaging spectrometer (HIRIS) for EOS requires development of a 128 × 128 ft focal plane array for the 2-2.5 micrometer band.

EOS, typical of future instrumentation requirements, will generate a greater volume of data at a higher rate (300 to perhaps 600 MB/sec) than any previous mission. In order to reduce the downlink requirements to manageable levels, to ease the ground data handling problems, and to enable both reprogramming on-board and real-time readout of science and operations (e.g., the broadcasting of icebergs or winds to ships at sea), a new capability of high-rate, on-board processing must be developed. Once developed, the technology may be applied to future NASA missions. The required developments include a VHSIC-like flight array processor, a general purpose high-speed computer, and advanced

compression techniques for the generated data of the instruments (e.g., HIRIS, SAR). Requirements are still being defined regarding the extent of on-board autonomy. This thrust may lead to a need for a space-qualified symbolics-type machine.

The polar platforms require bulk data storage devices that will hold between 2×10^{11} and 10^{12} bits of storage and that can handle data at 150 MB/sec and 300 MB/sec. (As the technologies of SAR and HIRIS develop, high-rate recording equipment use will also extend into the free-flyer programs.) These devices should also be capable of 20,000 read/write cycles to achieve the required life. No present optical system can approach these requirements in the required time frame. Nevertheless, future effort for incorporation of this technology should be pursued.

EOS is expected to operate for 20 years with service visits every two or three years. Therefore, to avoid unacceptable breaks in observation or loss of a platform between visits, EOS must have the capability to analyze its own status, detect anomalies, and possess the ability to activate redundant systems or devise a work-around of malfunctioning systems.

Large Deployable Reflector (1990s)

The LDR is an astronomical observatory designed to operate in the spectral region between 30 and 1,000 micrometers. The astronomy and astrophysics study chaired by Dr. George Field recommended a launch of LDR in the late 1980s.[9] It is roughly 10 times the size of the HST, 20 m versus 2.4 m in diameter. Unlike EOS it is not designed to fit inside the Shuttle's cargo bay but rather to be carried into space in parts and assembled at the Space Station. After assembly it will be boosted to a 700 km orbit where it will operate as a free-flyer. The mass of the system in orbit will be 20,000 kg and will require about 10 kW continuous power.

The 20 m diameter primary mirror of the LDR consists of 84 hexagonal panels, each panel roughly 2 m and made of lightweight composite materials. The primary mirror is to provide diffraction-limited performance at 50 micrometers. Some of the instruments are to be cooled to liquid helium temperatures, others only to liquid nitrogen temperatures. The observatory is to have a 20-year life.

Several Phase B studies and a number of scientific and technical workshops have been conducted to create a conceptual design and

identify the critical technology developments required to support the LDR.[10] Figure 3 is an artist's concept of LDR in orbit.

Control systems technology is crucial to LDR. LDR requires 0.05 arc sec absolute pointing accuracy and less than 0.02 arc sec jitter. It requires active alignment, figure, and vibration control of the optical system to a tolerance of 1 micrometer. The position and orientation of all 84 segments of the primary mirror must be actively controlled to provide diffraction-limited performance at 50 micrometers. Scan modulation (spatial chopping) will be required to reduce background noise by a factor of a million.

The structure of the primary reflector is a major challenge to materials and fabrication technology. The individual 2 m panels require a weight per unit area in the range 6-10 kg/m^2. Thermal control is a formidable challenge, the primary mirror must be maintained at 200°K with a variation across the primary of less than 1°K.

LDR science instrument needs can be classified into two general categories, submillimeter wave heterodyne technology and far-infrared direct-detection technology. Critical components in the former category are mixers, local oscillators, amplifiers, and spectrometers. Super-conductor, insulator-superconductor, and photoconductor mixers show promise for the lowest and highest submillimeter frequencies, respectively, in the LDR domain. These technologies should also be applied to the development of arrays that are essential for the efficient use of LDR's observational resources. In the area of direct-detection sensors, the major need is for instruments with large arrays operating at high backgrounds. New concepts in long-wavelength focal planes and readouts, and improved signal processing electronics, are also required.

Cryogenic cooling of the instruments requires a substantial advance in technology. A decision must be made as to whether to use stored cryogens or an active refrigerator to maintain the temperature of the instrument during the one to three years between visits.

Mars Sample Return Mission (1990s)

The purpose of a MSR mission is to obtain samples at several depths, at widely dispersed sites on the Martian surface, and to maintain the samples in a pristine condition while returning them

FIGURE 3 Artist's concept of Large Deployable Reflector. *Courtesy of NASA.*

to Earth for analysis. In addition, the roving vehicle would measure several physical properties of each site (such as the local magnetic, gravitational, and electric fields) and implant detectors (seismic and meteorological) at some of the sites to form a network to study Martian seismic activity and weather patterns.

The Space Science Board in its report, *Space Science in the Twenty-First Century*, recommends the use of roving vehicles to explore and analyze the Martian surface and a Martian sample as part of a program focused on the exploration of Mars.[1] Because of its cost the MSR mission was not included in the report, *Planetary Exploration Through Year 2000*, prepared by the Solar System Exploration Committee.[2] The Soviets are planning to launch a mission in 1988 that will use a rover to explore and sample the surface of the Martian moon, Phobos. They have announced their intent to follow that mission with a sample return mission in the late 1990s and manned exploration of the red planet early in the next century. There is a high probability of the United States proceeding with MSR because of its intrinsic interest and the charge to NASA in the Space Act to maintain U.S. leadership in science and technology.

The MSR mission has been studied for over a decade.[10] Figure 4 shows the mission scenario for MSR. To reduce weight and cost of the mission, the entire Martian system (orbiter, lander, rover, and launcher) will briefly enter the Martian atmosphere to slow its speed to Martian orbital velocity. After exit from the Martian atmosphere, the orbiter will detach and go into Martian orbit and the rest of the system will reenter the Martian atmosphere to land on the Martian surface via a parachute and rocket system. Figure 5 shows the details of this "aerocapture" maneuver. Figure 6 is an artist's concept of the lander, rover, and the combined sample return system and launcher on the surface of Mars.

MSR will be a major driver of guidance and navigation technology. The aerocapture corridor on Mars is approximately 20 km thick; this is the separation between the top of the Martian terrain and the "bottom" of the Martian atmosphere. The bottom of the atmosphere is defined as the altitude above which the aerodynamic controllability of the spacecraft is lost. There is considerable uncertainty in the variation of the atmospheric density with altitude and time on Mars. Therefore, the guidance and control system must fly down the middle of this corridor and do so without human help from Earth; the aerocapture vehicle will experience radio blackout

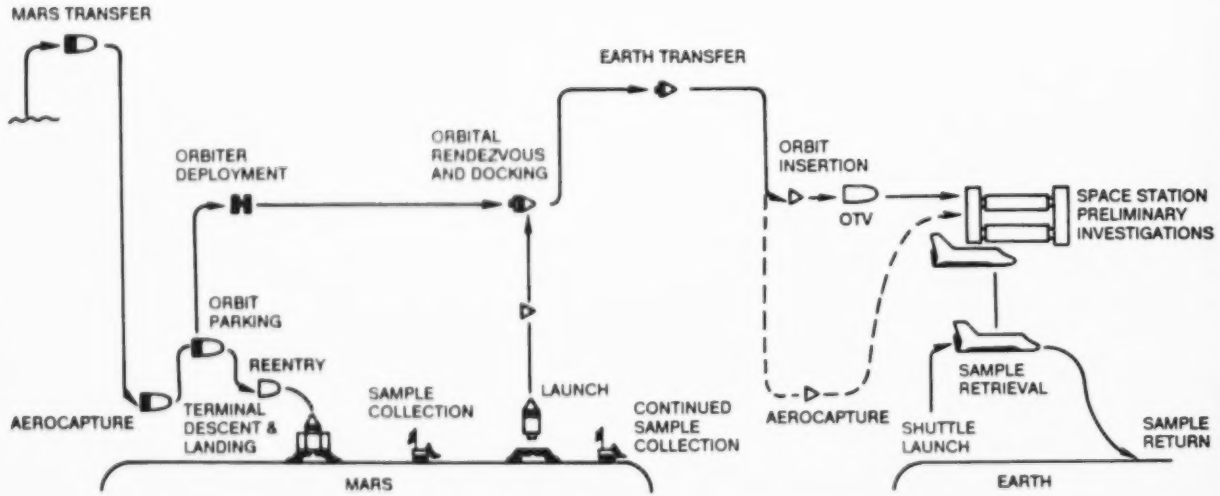

FIGURE 4 Mars Sample Return single-launch mission scenario.

during the entire first pass through the atmosphere. Once in orbit the lander must be guided through the atmosphere to a 5 × 5 km landing site. The guidance and navigation system must have an autonomous system to detect and avoid landing obstacles. Round trip transmission times preclude intervention or control from Earth. The Viking spacecraft flew blind onto the most bland and hazard-free sites that could be located on Mars. MSR will undoubtedly want to land at the most interesting and, quite possibly, hazardous sites.

Once safely on the Martian surface the guidance and navigation system (GNS) must guide the rover on a 400-day, 200 km trek across the surface of Mars and back to the landing site for rendezvous with the launcher and transfer of the samples to the launcher. The GNS must then take the launcher from the surface of Mars to an autonomous rendezvous with the orbiter, transfer the samples from the launcher to the orbiter, and then guide the orbiter from Mars orbit back to Earth orbit for a final rendezvous with the Shuttle or Space Station.

MSR provides a major challenge to autonomous sample gathering. Drills will be required for sampling beneath the surface. Some onsite samples analysis will be required.

MSR requires transmission of about 100 Mb of data per day to the Earth. The rover requires about 1 kW of continuous power while moving. Existing and planned nuclear power supplies cannot provide this much power and remain within the mass constraints of the rover.

MSR will require autonomous systems to detect and correct, replace or devise work-arounds for malfunctioning components.

The Mars rover is a major driver for robotics and autonomous operation. It is a major enabling technology for exploration of any hard surface.

LONG-RANGE SPACE SCIENCE TECHNOLOGY REQUIREMENTS

The committee examined the long-range space science technology requirements in two ways, by looking at long-term trends and examining seven challenging missions that might be undertaken in the first quarter of the twenty-first century.

Astronomers will want to improve resolution from the 0.01 arc

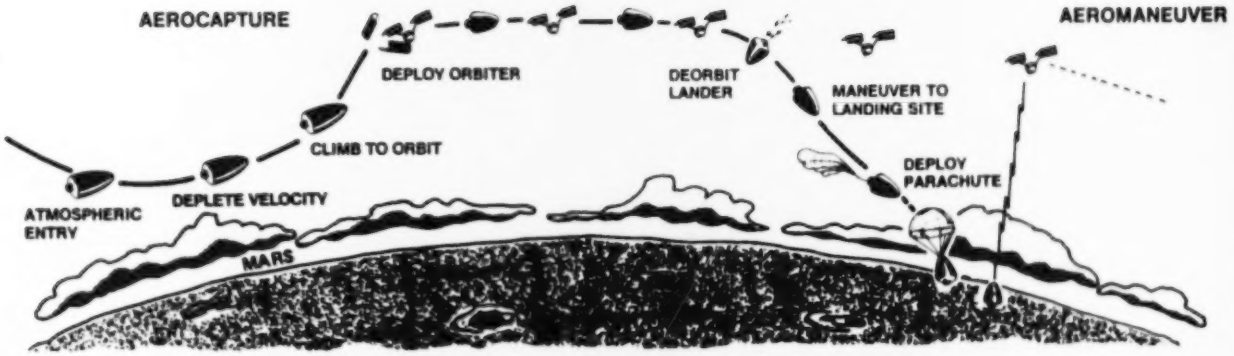

FIGURE 5 Mars Sample Return mission single-launch mission with aerocapture/aeromaneuver.

sec of the HST and LDR to milli-arc sec at the beginning of the century and on to micro-arc sec by 2025. They will want to increase their collection areas in the optical range from the 4 m^2 of the HST to 200 m^2 and increase their aperture to 100 m. They intend to increase their resolution through the use of interferometers, developing optical interferometers with baselines growing from hundreds of meters to hundreds of kilometers. One of the seven missions discussed below envisions an interferometer of 1,000 astronomical units, roughly 1.5 billion km.

Solar and plasma physicists propose to probe the outer atmosphere of the Sun. Such a solar probe requires substantial development of heat protection systems. Probes to the nearest star will drive propulsion and communications technology.

Astrophysicists are attempting to detect gravitational waves. When they are detected and understood, their nature will strongly influence relativity experiments. Similarly, the results from Gravity Probe-B will strongly influence the direction of scientific research and highly challenge technologies of this discipline.

Beyond sample return from Mars, planetary scientists will want sample returns from Venus, asteroids, and comets. They will want observational networks on the terrestrial planets and orbiters and probers of the outer planets. Human exploration of Mars could be the major driver of technology for the next quarter century. Cost and complexity of human exploration of the planet raises two fundamental issues, will the United States ever undertake such a mission and, if so, will they undertake it alone or as a part of an international consortium.

The direction of the scientific research and, hence, the technology requirements for manned laboratories in space beyond those being planned for the Space Station will be determined by the discoveries made on Shuttle flights and early in the life of the Space Station and by the decision on human exploration of Mars. If the decision is made to go to, or to be ready to go to, Mars, then long-duration human flight will drive life science and its technology requirements. Similarly, the results of materials science research over the same time period will determine the technology needs for that discipline.

FIGURE 6 Artist's concept of the lander, rover, and combined sample return system and launcher on the surface of Mars. *Courtesy of NASA.*

TWENTY-FIRST CENTURY SPACE SCIENCE TECHNOLOGY DRIVER MISSIONS

The seven missions selected as technology drivers for the first quarter of the twenty-first century are concepts, not well-studied missions such as the three chosen for the mid-1990s. They may not be feasible since they depend upon orders of magnitude improvement in the ability to point, stabilize, and measure the distance between spacecraft. In other cases the energy requirements may rule them out until a major scientific or technical breakthrough occurs. Others require "gossamer" structures whose behavior in space cannot be predicted with existing theoretical and mathematical tools. They are, however, indicative of the trends in space technology toward large-area, low-density structures, pushing guidance and control systems to their ultimate limit, and the development of systems capable of detecting and repairing their own malfunctions.

Coherent System of Modular Imaging Collectors

Figure 7 shows the concept and illustrates the level of analysis behind the Coherent System of Modular Imaging Collectors (COSMIC). Nine 1-2 m (HST class), diffraction-limited telescopes are arrayed along a 100 m tetrahedral structure. Such a system provides the resolution of a 100 m diffraction-limited telescope and a 40 m^2 collecting area; an increase of about a factor of 40 in resolution and 9 in collecting area over the HST. It substantially extends, and its initiation will depend upon the successful demonstration of, the technology required for the LDR.

COSMIC Interferometer

Two COSMICs separated by 100 km create an interferometer with a resolution of about 10^{-6} arc sec (4.85×10^{-12} radians). (A 0.5 mm lead at 100,000 km subtends an angle of 10^{-12} radians.) Such a system will challenge the technologies of structural control and station keeping.

Solar Probe

Scientists propose to send a probe to within four solar radii of the Sun for solar studies and general relativity effects from the solar

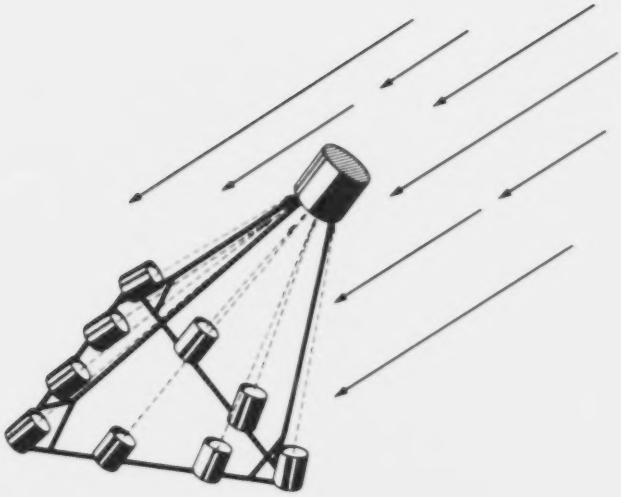

FIGURE 7 Astronomer's concept of COSMIC, a space telescope array with nine 2-meter class telescopes on a 100-meter tetrahedral truss.

gravitational field. Such a mission requires a substantial advance in thermal shields and in the ability to provide a drag-free environment for the test mass in the probe.

Venus Sample Return

A Venus sample return mission also requires a substantial advance in thermal control as well as the ability to withstand high pressures and to launch a spacecraft from the surface of Venus through its very dense atmosphere and into orbit.

Thousand Astronomical Unit Mission

Astronomers propose using nuclear propulsion to transport a meter-class optical telescope to a distance of 1,000 astronautical units from the Earth. Lasers would be used to measure the separation between this system and a COSMIC system in Earth orbit and to communicate with the system, thereby creating an Ultra Long Baseline Optical Interferometer.

Colonies on the Moon and Human Exploration of Mars

The report of the Presidential Commission on Space[5] calls for lunar colonies and human exploration of Mars. Such activity challenges almost all disciplines of space technology, particularly closed-cycle life support systems and systems to enable humans to live and work in the space environment.

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3
Defense Space Research and Development Requirements and Technology Drivers

Space systems provide critical functional support to U.S. military forces in the areas of communications, navigation, weather monitoring, Intercontinental Ballistic Missile (ICBM) surveillance, and attack warning. In some instances, military technology requirements differ from those of the civil and commercial sectors, but in many cases the projected requirements overlap. The Space Act of 1958 recognized that fact and assigned NASA a role in developing dual-use space technology which can have both civil and military applications. Reliable, affordable launch capability is both an immediate and long-term defense requirement and was addressed earlier in the discussion of space transportation mission sets.

In communications, under both current and planned systems,* the technology issues are and will continue to be (a) survivability and connectivity, (b) traffic volume and bandwidth, and (c) provisions for reducing communications exploitation susceptibility.

In navigation, the TRANSIT system has been the navigation

*Current military communication systems include the Defense Satellite Communications System, Fleetsatcom, LeaseSat, AFSatCom, and the Satellite Data System. Milstar and Submarine Laser Communication are planned future systems.

standard since the early 1960s. By the early 1990s the NAVSTAR Global Positioning Satellite System, which was conceived in the 1960s, will become operational. The advanced technology issues in satellite navigation related to GPS concern (a) system autonomy and survivability, (b) user equipment cost and performance, (c) effective antijam protection, and (d) potential for commercial applications, particularly to instrument landing.

In meteorology, the Defense Meteorological Satellite Program (DMSP) complements the civil TIROS-class program and provides cloud-cover monitoring and atmospheric parameter measurements for tactical military uses, although the DMSP tactical terminals are not widely used. Future planned systems include remote ocean monitoring (the Navy Remote Ocean Sensing Satellite [NROSS] system), which could be used for providing data useful for aiding submarine detection and obtaining information on ocean surface waves, surface winds, and broad-ocean-area gravity anomaly data. Direct transmission meteorological satellite data is generally useful but not critical at the tactical level, because forecasts and other information are available through conventional terrestrial communication sources. Since meteorological satellite (MetSat) data is viewed as "nice to have" it does not provide technology "drivers" related to DOD missions.

For ballistic missile attack warning and assessment, the current Defense Support Program Satellite System and planned future systems rely on technologies which have common heritage with civil space science and remote sensing missions. Examples of dual-use technologies are (a) advances in techniques reducing false-alarm rates, (b) on-board processing to reduce the need for wideband data links, and (c) advanced clutter rejection image processing algorithms. There is also a need to improve ground station survivability. Advanced infrared (IR) sensor development and high capacity space data processors are key to improvements in this area. Civil developments in infrared astronomy and planned research on advanced space computers may find common application in these areas.

Regarding space launch, because of the need for launch dependability, the Air Force will continue to procure expendable launch vehicles to meet immediate needs. Future improvements will be called for in the area of launch costs and system survivability. As noted in the above discussion of space transportation, NASA and DOD are committed to develop an Aerospace Plane that could play many

distant future military roles, including high-performance and low-cost space transportation; a global range remote sensor platform; a fleet defense interceptor deployed from the continental United States; and a survivable space launcher, which could be deployed to dispersed bases for reconstitution of LEO space assets following antisatellite (ASAT) attack.

NEW MISSIONS AND THEIR TECHNOLOGY REQUIREMENTS

The following four mission areas are seen as requiring substantial technology advances for defense as well as civil applications. The technologies listed are those in which NASA might make contributions through development of dual-use space qualified systems, sub-systems, and devices. It is not suggested that NASA take the lead in developing technologies in these areas, but rather that it select those technologies in which it has correlating interests and work jointly with DOD to assure timely development and application in both civil and military systems.

Strategic Communications and Related Radio Frequency Space Applications

Military and civil communications have a common technology basis. Common needs include techniques for rejection of co-channel interference, increased resistance of space-based components to space radiation, the ability to move to higher frequencies for increased bandwidth availability and for higher gain, and electronically switched beams for higher directivity.

Applicable illustrative technology advances may include gallium arsenide digital integrated circuits, lower cost monolithic microwave integrated circuits, affordable phased array antenna modules, low-cost atomic frequency standards for spread spectrum code synchronization for acquisition, and practical space-to-space and space-to-ground laser communication.

Ocean Remote Sensing for Oceanographic and Meteorological Ocean Surface Interaction Data

Information about the state of the ocean depths and ocean surface have both military and civil applications. Common interests

include ocean surface wave states for shipping and route planning; ocean temperature, salinity, turbidity, and gradients thereof for antisubmarine warfare and fish location as well as long-term ocean research; and high resolution sensing of the ocean surface by radiometry and radar for severe storm forecasting and surface wave observations.

Technologies needed for these remote sensing missions are large diameter, high precision antennas for millimeter wave radiometry; millimeter wave RF components at Ku band, 94 GHz, and 140 GHz frequencies; laser and optical spectrometers for both atmospheric and submarine diagnostics; radar X-band and Ku band space qualified high power components; practical affordable phased array antennas; phase shifters; and high-capacity space-qualified signal processors.

Low-Cost Satellite Systems and Subsystems for Low-Cost, Near-Earth Applications

Since the Challenger accident, the space science community has been speaking out for a return to low-cost "Explorer class" missions carried into space on less costly expendable launch vehicles. Meanwhile, the Defense Advanced Research Projects Agency (DARPA) has begun a program to explore the military utility of low-cost satellites deployed in near-earth orbits to satisfy DOD needs. One such concept is a low-cost multiple satellite system. These separate needs demonstrate a convergence of interest between NASA and DOD.

Common technologies which could be emphasized in this area are (1) low-cost satellite subsystems including power and power conditioning, attitude control and stabilization, command and data handling, and low-cost structure; (2) lower-cost integration and management technologies; and (3) low-cost expendable launch vehicles to place 300 lb to 500 lb in 500 nautical miles low-earth orbit.

Strategic Defense

Although DOD is investing $3B to $5B per year in strategic defense research, much of it applied to space mission concepts, there are overlapping areas of interest where NASA and DOD working together on technology developments could be beneficial. Some

major technology interests for strategic defense which have elements of common threads for future NASA and other civil missions are:

- Low-cost heavy-lift space transportation ($10 to $100 per pound to LEO)
- Space power of 100 kW to 1 MWe continuous with 10-second pulsed requirements of 100 MWe
- Netted or distributed control system architecture
- Distributed data bases and concepts to access them
- Autonomous spacecraft operation over decades of time
- Orbital repair and refurbishment
- Low cost orbit-to-orbit transfer
- Large, precise optical systems for space deployment
- Intelligent computer-human interfaces
- Image understanding and other artificial intelligence applications

NASA'S ROLE IN ADDRESSING DEFENSE SPACE TECHNOLOGY NEEDS

NASA's role might be seen as coordination, anticipation of need, and creation of new opportunities in those military mission areas where dual-use technology interests exist. A number of committees and liaison offices, such as the Senior Interagency Group/Space, Aeronautics and Astronautics Coordinating Board (AACB), NASA's Military Liaison Office, and the Space Transportation System (STS) Liaison Office at the Air Force Space Division, are designed to coordinate NASA and DOD activities in space technology research and development. Nevertheless, research coordination could be improved with benefits for both organizations. The committee agreed that the missions of both NASA and the DOD would be enhanced were cooperation between the two strengthened at top levels of management, at mid-levels, and at the working level.

In 1982, the budget for the defense space program exceeded that of NASA for the first time, and the gap has continued to widen. However, with the exception of DARPA and the Strategic Defense Initiative (SDI), most DOD funding for space is earmarked for development and operations. The NASA role, chartered by the Space Act, is to develop generic space technology for all U.S. space interests.

To carry out this responsibility, those parts of NASA concerned with advanced space technology development need a clear understanding of future DOD missions. At the same time, NASA programs could benefit by an enhanced exchange of information regarding work being conducted within the DOD. Better mechanisms are needed to ensure exchange of information between DOD and NASA about desired future "technical goals" for space research. This might include a clear policy statement by DOD leadership concerning the value of NASA opportunity-generating basic research. NASA, on its part, should exert a greater effort toward working closely with the DOD to anticipate long-term defense technology needs in areas such as rocket propulsion, laser communications, spacecraft autonomy, and advanced materials.

NASA also might help create new defense opportunities by moving ahead in high-performance spacecraft subsystems; large, actively-controlled space structures; and orbital refurbishment and supply.

4
Humans in Space

Human presence in space is taken as axiomatic for this analysis. National decisions regarding the purposes and extent of that presence must, of course, rest with the President and the Congress. But for any human venture in space, it is essential that operation be both safe and efficient. Those undertaking manned missions must be able to perform effectively their responsibilities in a space environment and react effectively to unexpected and unanticipated occurrences.

Studies of humans in space have been extensive—from the report of the National Commission on Space,[1] to lay descriptions of the Soviet manned space activities,[2] and to NASA-commissioned research reports and overviews, such as *Living Aloft*.[3] However, all seem to agree that an increased level of research concerning all aspects of man in space is critical. Not enough is known about the physiological, psychological, and sociological aspects of humans in space. Further, life support aspects are critical, as are local mobility aids and propulsion and power-supply considerations.

The "Twelve Technological Milestones in Space" that appear as goals of the NCOS serve as a useful point of departure because all potentially involve man. They are:

1. Initial operation of a permanent Space Station.

2. Initial operation of dramatically lower-cost transport vehicles to and from low Earth orbit for cargo and passengers.

3. Addition of modular transfer vehicles capable of moving cargoes and people from LEO to any destination in the inner solar system.

4. A spaceport in LEO.

5. Operation of an initial lunar outpost and pilot production of rocket propellant.

6. Initial operation of a nuclear-electric vehicle for high-energy missions to the outer planets.

7. First shipment of shielding mass from the Moon.

8. Deployment of a spaceport in lunar orbit to support expanding human operations on the Moon.

9. Initial operation of an Earth-Mars transportation system for robotic precursor missions to Mars.

10. First flight of a cycling spaceship to open continuing passenger transport between Earth orbit and Mars orbit.

11. Human exploration and prospecting from astronaut outposts on Phobos, Deimos, and Mars.

12. Start-up of the first Martian resource development base to provide oxygen, water, food, construction materials, and rocket propellants.

The Mars missions undoubtedly require the most significant technology development. For the purposes of this report, other potential missions, such as the LEO Space Station and a manned lunar port, can all be considered subsets of this undertaking. Needless to say, the knowledge acquired in the Space Station will be essential to enable more challenging manned missions.

EARLIER MISSIONS: THE SPACE STATION AT LEO—1990s

The U.S. expects to assemble and occupy a Space Station in LEO in the mid- to late-1990s. Extended research concerning humans in space and the effects of long-duration presence in outer space is needed, both in the Station and in terrestrial activities. In space, the continued effects of space radiation and low gravity and the implications of artificial gravity must be studied. Not only do we need to know the effects of zero g, but it is important to study prolonged exposure to one-sixth and one-third g. Better space suits, local tooling for extravehicular activities (EVA), and small

"space taxis" are needed. Robotics will require special attention, with emphasis on the interaction with humans and on training and adapting aspects. Simulation of all of these aspects on Earth will be necessary along with controlled experiments in space. A data base should be begun on the psychological, as well as physiological, aspects of longer human space presence. All of these are discussed in subsequent sections.

MID-TERM MISSION: RETURN TO THE MOON—2005

With respect to establishing a Moon base or port, shielding from solar radiation and cognizance of the effects of prolonged low gravity and weightlessness become critical. By the time man can be based on the Moon, the results of unmanned, but expert, missions to the Moon should be available. The feasibility of bringing shielding material from the lunar surface to LEO can be investigated, as well as the possibility of bringing back life-supporting and energy-producing materials. The use of nuclear power sources could efficiently address energy requirements for long stays on LEO and on the Moon.

LONG-TERM MISSION: MARS—2015

As noted, a manned Mars mission has great potential to stress technology development. For that reason, this mission is used as a model to indicate technology development needs. An initial manned mission to Mars can be anticipated only after a logical progression of missions, although planning for the manned mission should take place simultaneously with such missions as return to the Moon and a Mars sample return mission. The following are seen as areas for concentrated technology development:

- Life support effects of micro and variable gravity; complete closure of the environmental loop; radiation shielding and countermeasure; and productive, health-sustaining activities for long-duration missions.
- Human productivity—mobility aids for EVA; telepresence; robotics; AI; and suits and tools.

- Space transportation and power needs; significantly shortened travel time in space using high Isp, high-thrust engines, or multimegawatt nuclear-electric propulsion engines; reduction of on-orbit fuel delivery costs by a factor of 2 to 4; hybrid propulsion/power supply system for long-life, reliable, robust power for life support and other mission-critical power requirements en route; and power supplies for activities on the Martian surface (the SP-100 class of power is appropriate here).
- Utilization of indigenous extraterrestrial resources for life support, construction materials, and fuels.

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Part II:
Enabling Technologies

5
Propulsion

BACKGROUND

With the hiatus in the national manned space program at the end of the Apollo program, propulsion technology development shifted from a broad-based set of activities and facilities to a very narrow focus on Space Shuttle Main Engine (SSME) development. No other significantly advanced propulsion technologies have been seriously studied in the United States for the past 20 years. The nation successfully developed and deployed a whole series of Saturn heavy-lift vehicles but has since lost the wherewithal to regenerate easily that capability.

Another example of a major program termination occurred when the Direct Nuclear Propulsion Development Program, (ROVER/NERVA),[1] which was begun in 1950, ended in 1973. Nearly $1.5 billion had been expended over a 20-year period, culminating in 20 full-scale engine tests[2] at the Nevada Test Site. The program was declared a complete technical success, but was terminated due to economic problems and the absence of hard mission requirements.

When these and other similar propulsion programs were terminated, much of the technology base was lost. Termination was abrupt and documentation of the status of the technology was left

either incomplete or decentralized. In addition, much of the capability required to succeed in such propulsion programs resides in the minds of the individual scientists and engineers who developed the "art" of their respective disciplines. For example, the successful production, qualification, process engineering, manufacturing techniques, and welding techniques for refractory alloys has largely been lost because much of the discipline resides in the memories of now retiring scientists, metallurgists, and engineers.

In addition, between the time that the nation's propulsion R&D program (other than SSME) was terminated and today, many of the facilities that would be required for technology development for advanced engines have been either closed down, mothballed, or are now in use for other purposes. Specific examples include the Nuclear Rocket Development Station (NRDS) at the Nevada Test Site, rocket engine test facilities at the Marshall Space Flight Center and Edwards Air Force Base, supersonic large-scale wind tunnels, and materials development and refractory alloy laboratories. To reinvigorate the nation's nuclear propulsion R&D program, it will be necessary to reestablish the key disciplines, to restore or rebuild many of the major testing facilities, and to recapture the lost technical and institutional infrastructure. In short, we must virtually start over.

STATUS

Technology development continues on the next-generation Shuttle engine technology, and work is just beginning on the technology required for air-breathing engines of the sort envisioned for the National Aerospace Plane.

NASA, in its Civil Space Technology Initiative (CSTI),[3] is expanding its R&D work on LOX-H_2 Earth-to-orbit engines to include expanded R&D in the areas of LOX-hydrocarbon and dual-fuel engines for Earth-to-orbit propulsion. Technology development is continuing at a modest level for (1) advanced cryogenic engines for orbital transfer, (2) cryogenic fluid management and storage technology for in-space servicing, and (3) auxiliary propulsion for several classes of spacecraft (scientific, military, and commercial) requiring orbit adjustment, attitude control, station keeping, and maneuvering. This includes advanced storable, electrothermal, electric, and hydrogen-oxygen devices. The emphasis in these technology

areas is best characterized as providing incremental performance improvements rather than major breakthroughs.

In Fiscal Year 1987, and as a result of the Air Force Forecast II program, Air Force Systems Command decided to reinitiate a Direct Nuclear Propulsion program[4] similar to the ROVER program referred to in Table 2.* The initial goals of this program are to develop high Isp, high-thrust, low-weight propulsion system options for engine ground testing within the next five years. Both a ROVER derivative system and an advanced system are envisioned for full-scale engine testing. The Air Force is interested in direct nuclear propulsion for orbital transfer vehicles (OTVs), fast launch interceptors, upper stage intercontinental ballistic missiles (ICBMs), and other missions. The initial program is likely to concentrate on the OTV.

Both the National Aerospace Plane and the Air Force Forecast II nuclear propulsion program will be strongly driven by DOD requirements. NASA supports the SP-100 program[5] in power-supply technology ground demonstration that also can apply to a Strategic Defense Initiative (SDI) nuclear-electric propulsion mission. The ground rule that has been adopted for the SP-100 nuclear-electric propulsion flight demonstration (1990s) is to utilize thruster technology that has low risk and that has been demonstrated in the past. Consequently, the system will probably use one of the arcjet thrusters developed in the 1960s. Currently, there is no plan to support an R&D program to advance the state of the art of nuclear-electric propulsion systems.

OPPORTUNITIES

An opportunity exists to build almost from scratch an advanced propulsion technology development program that meets many different needs for the future. As discussed in Part I regarding space transportation, there are several general areas that require research to enable the aggressive exploration of space. First, both DOD and NASA requirements dictate the need for a heavy-lift launch vehicle (in the range of 150,000 lb payloads) in the mid-1990s time frame. An aggressively focused technology program, building on the current research and technology development base effort, could lead

*Between 1955 and 1973 more than $3 billion was spent on the nuclear power and propulsion programs shown in the table.

TABLE 2 Principal U.S. Space Reactor Programs

Power Plant	Purpose	Power Level	Operating Temperature (K)	Period	Type of Reactor	Fuel	Converter	Development Level
Rover	Propulsion	365-5,000 MW(t)	2,450	1955-1973	Epithermal	UC	--	Twenty reactors tested. Demonstrated all components of flight engine for more than 2 h. Ready for flight engine development.
Fluidized-Bed reactor	Propulsion	1,000 MW(t)	3,000	1958-1973	Thermal	UC-ZrC	--	Cold flow, bed dynamics experiments successful.
Gaseous-core reactors	Propulsion	4,600 MW(t)	10,000	1958-1978	Fast	Uranium plasma, UF_6	--	Successful critical assembly of UF_6.
			1,500				Brayton	
	Electricity	4,600 MW(t)	10,000	1959-1978	Fast	Uranium plasma UF_6	--	Successful critical assembly of UF_6.
			1,500				Brayton	
SNAP-2	Electricity	3 kW(e)	920	1957-1963	Thermal	Uranium zirconium hydride	Mercury Rankine	Development level. Tested two reactors; longest test reactor operated 10,500 h. Precursor for SNAP-8 and -10A.
SNAP-10A	Electricity	0.5 kW(e)	810	1960-1966	Thermal	Uranium zirconium hydride	Thermo-electric	Flight-tested reactor, 43 days. Tested reactor with thermo-electrics in 417-day ground test.
SNAP-8	Electricity	30-60 kW(e)	975	1960-1970	Thermal	Uranium zirconium hydride	Mercury Rankine	Tested two reactors. Demonstrated 1-yr operation. Nonnuclear components operated 10,000 h and breadboard 8,700 h.

TABLE 2 Principal U.S. Space Reactor Programs (continued)

Power Plant	Purpose	Power Level	Operating Temperature (K)	Period	Type of Reactor	Fuel	Converter	Development Level
Advanced hydride reactors	Electricity	5 kW(e)	920	1970-1973	Thermal	Uranium zirconium hydride	Thermo-electric and Brayton	PbTe thermoelectrics tested to 42,000 h.
SNAP-50	Electricity	300-1,200 kW(e)	1,365	1962-1965	Fast	UN, UC	Potassium Rankine	Fuels tested to 5,000 h.
Advanced metal-cooled reactor	Electricity	300 kW(e)	1,480	1965-1973	Fast	Uranium nitride	Brayton and potassium Rankine	Nonnuclear potassium Rankine cycle components demonstrated to 10,000 h. Ready for breadboard loop.
710 gas reactor	Electricity and propulsion	200 kW(e)	1,445	1962-1968	Fast	UO_2	Brayton	Fuel element tested to 7,000.
In-core thermionic reactor	Electricity	5-250 kW(e)	2,000	1959-1973	Fast or thermal driver	UO_2 UC-ZrC	In-core thermionics	Integral fuel element, thermionic diode demonstrated for more than 1-yr operation.
Nuclear electric propulsion	Electricity	400 kW(e)	1,675	1974-1981	Fast	UO_2	Out-of-core thermionics	Limited testing on thermionic elements.
SPAR/SP-100	Electricity	100 kW(e)	1,400	1979-present	Fast	UO_2, UN	Thermo-electric	Limited testing on core heat pipes and advanced thermoelectric materials.

to great benefits when the payload requirements arrive. Second, NASA has the opportunity now to turn toward the development of advanced reusable manned vehicles (e.g., Shuttle-II and the National Aerospace Plane). Third, NASA is in a unique position to support R&D that will dramatically increase the reliability of Earth-to-orbit engines. NASA laboratories and their contractors together have the technical capability to tackle this job. Industry alone has neither the capability nor the money to take this on.

Another opportunity exists for NASA to begin R&D toward development of an OTV capability with a possible goal of moving a 20,000 lb payload from low-Earth orbit to either sun-synchronous or geosynchronous orbit.

For the heavy-lift launch vehicle, advanced manned vehicle, and OTV, technology that would enable reusability would dramatically increase the nation's capability and provide offsetting financial benefits that would pay for the R&D program many times over (see Appendix A).

R&D started now for missions requiring high-energy transfers (e.g., interplanetary and outerplanetary missions) will enable NASA to conduct the advanced scientific experiments at the time such missions are envisioned (mid- to late-1990s).

Nuclear-electric propulsion is again a highly desirable if not enabling technology for scientific missions of this sort or for even more aggressive and higher energy orbit transfers, such as the manned Mars mission. An opportunity exists for NASA to team with the Air Force to develop direct-thrust nuclear propulsion. This technology may become key beyond the year 2000 for an advanced OTV to meet NASA, SDI, and military requirements as well. It will require refurbishment of existing facilities such as those at the Nevada Test Site and the addition of special effluent handling systems if full-power life testing on the ground is required. Environmental and safety concerns dictate the development of innovative systems, e.g., ones that can be launched in pieces and assembled in space.

POTENTIAL PAYOFF

Propulsion research has been a pacing item for flight throughout the history of the space program. Propulsion systems normally require both a long development cycle (10-15 years) and have high initial costs (billions of dollars). It has also traditionally been a

leading edge technology requiring advances in high-temperature materials and structures, lightweight structures, and many other technology areas. These advanced technology efforts usually become synergistic with other technologies required for overall space exploration.

The financial payoff of R&D in advanced propulsion systems is large. Since a significant portion of the cost of placing satellites on orbit depends on launch vehicle and on-orbit fuel costs, major reductions in launch, orbital transfer, and other expenses can make viable civil and military satellite programs that would otherwise be prohibitively expensive. Launch of the many millions of pounds, for example, that would be required for virtually all user* scenarios may only be affordable if advanced propulsion systems can be made available. Whether or not SDI is deployed, similar arguments can be made for other military satellite programs that require placing many massive satellites on orbit. Direct-thrust nuclear propulsion, e.g., for a manned Mars mission, deployed from LEO could save up to $5 billion in costs for transportation from the ground to LEO† compared to a total mission cost of $25 billion to $30 billion.[6]

Advanced technology investment in low-thrust auxiliary propulsion can contribute to a substantial increase in payload mass fraction for a wide range of scientific, military, and commercial spacecraft. Integrating advanced thrusters with parallel advances in other subsystems of the spacecraft bus (power system, thermal management, structure, and on-board control) can lead to a reduction of more than one-third in bus mass. This can lead to a doubling of payload mass in many cases.

Further, emphasis on increasing the life and reliability of chemical propulsion systems has payoffs comparable to those realized as a result of past investments in technology for life management of the gas turbine engine. In fact, engines for subsonic transport have focused upon lifetime and reliability rather than thrust-to-weight ratio in recent years. Life management technologies can be applied to the Shuttle main engines, for example, with overall gains in performance.

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*For example, Mars missions, Moon and Mars bases, SDI, and Air Force uses.

†The mass of a Mars mission vehicle is about 1.5 million lbs for a direct nuclear propulsion system compared to 4.5 million lbs for a chemical propulsion system.

Thus, the financial incentives to invest in an aggressive propulsion R&D program at this time are compelling.

It should be emphasized that the advantages in increased payload-to-liftoff mass and improved reliability that stem from use of advanced technologies should be made available for launch vehicles of all size classes. It is equally important that modern technologies be available for dedicated single-satellite or scientific requirements such as are now launched on Delta, Atlas, and Titan vehicles if the United States is to maintain a complete launch capability for such requirements.

ANTICIPATED CONSEQUENCES OF NO ACTION

There are no alternatives to initiating an aggressive propulsion R&D program if the nation expects to remain competitive in Earth-to-orbit and space transportation.

Because propulsion is a pacing item for the nation's space program, delays in initiating R&D for advanced propulsion systems concepts translate to a day-per-day delay in mission enablement. For example, a manned Mars mission envisioned for the late 1990s or early twenty-first century requires initiation of spacecraft main engine development today. If development is delayed for 10 years, for example, then the Mars mission will not be possible prior to the year 2010. Similar conclusions can be drawn for virtually all of the aggressive missions outlined by the NCOS. Delays will translate to the loss of U.S. space leadership to the European, Asian, and Soviet programs. Considerable impacts on the U.S. economy, prestige, and security could accrue (see Appendix A).

RECOMMENDATIONS

For the reasons stated above, advanced propulsion R&D should be afforded the highest priority in NASA's restructured R&D program. A new generation of technology should be pursued to support U.S. launch vehicle requirements, including a reusable OTV, Earth-to-orbit vehicles, and high specific impulse (I_{sp}) engines (nuclear-electric propulsion and direct nuclear thrust propulsion) with an eye toward reliability enhancements and cost reductions in each engine. NASA should become strong partners with other existing programs and tailor the R&D to support both DOD and civil mission needs.

Specifically, NASA should pursue engine design and development activities for:

- a range of advanced Earth-to-orbit engines (reusable, fault tolerant, reliable, economical) to accommodate the potential future launch vehicle fleet mix;
- reusable cryogenic OTV engine (fault tolerant, reliable, long-lived);
- high-thrust (greater than 10,000 lbs), high-performance (Isp greater than 860 sec) propulsion system for manned Mars and similar missions; and
- high-performance (Isp greater than 1,200 sec), low-thrust primary propulsion system for solar-system exploration spacecraft (nuclear-electric).

Since advanced propulsion should have the highest priority of R&D activity within NASA, the committee recommends that a substantial portion of any increase in the R&D budget be directed toward this technology base.

Major ground-based and/or flight-oriented system qualification tests of any of the propulsion systems mentioned above can quickly become more than NASA can afford within the scope of initiatives like the CSTI. The base technology (i.e., research) dollars should be kept separate from major vehicle development activities, as discussed in Part III, Conclusions and Observations. As the need for major system demonstrations and/or high-priority missions are identified by NASA, SDIO, or others, separate funding for hardware demonstration should be identified. For example, if NASA forecasts a manned Mars mission, it needs to initiate an engine development activity funded separately from the base technology program.

A revolutionary approach to advanced propulsion concepts is essential if the United States is to regain its world leadership position in space.

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6
Technology for Humans in Space

BACKGROUND

From the earliest suborbital Mercury missions to the present, the development of systems for protection of humans has been treated in a conservative manner, generally using well-proven technology with accompanying penalties in weight and performance. Only the major accidents—the Apollo fire and the Challenger tragedy—have produced reevaluations of crew support and protections.

The earliest concerns were related to g-protection, i.e, protection against the forces of gravity, especially the survival of astronauts during the high decelerations of atmospheric entry following exposure to weightlessness of hours to days. Anti-g suits and contoured couches proved adequate for reentry force protection and the problem was de-emphasized for the lower acceleration and longer duration Shuttle missions. In-flight exercise, fluid loading protocols, and suits for prevention of cardiovascular deconditioning have been pursued actively by the Soviets and to a lesser extent by the United States, largely on an ad hoc basis. Protection of the musculoskeletal system, while recognized as serious for long-duration missions, was not found to be critical for short Shuttle missions or expected to be of concern for Space Station tours of several months. Thus, in the

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late 1960s, NASA discontinued research on artificial gravity as not being necessary for planned missions.

The atmospheric makeup has oscillated among various total pressure levels based on engineering considerations. Rapid access to extravehicular activity (EVA) requires either a high-pressure suit or a low-pressure ambient atmosphere to minimize the prebreathing time needed to avoid bends. Fire safety considerations and the desire for normal physiological standards argue for a normal terrestrial atmosphere. Protection against solar and cosmic radiation is not a major problem for near equatorial, LEO missions protected by the Earth's magnetosphere, but threat evaluation and improved shielding are required beyond LEO.

STATUS

The presence of current Soviet space stations, the planned U.S. Space Station, and the anticipated long-duration exposures for a lunar base or manned Mars mission force reconsideration of g-protection, atmospheric makeup, and radiation protection issues.

The NCOS proposed several plans for the future national goals in space. Many of these involve the utilization of humans for operations and exploration in missions that challenge our abilities and require extension of our knowledge of the limits of human tolerance and recoverability from the rigors of long-duration flight. The information gained from the U.S. Skylab and Spacelab and the more recent Soviet long-duration flights leaves considerable doubt, but not excessive pessimism, as to the viability of humans in very long flights without the provision of extraordinary countermeasures.

The NCOS mission that stands as the yardstick is a manned round trip to Mars, with exploration on the surface, entailing in excess of three years with current propulsion systems. Prior to embarking on serious planning of this type of mission, human requirements and types of life support, including countermeasures against physiological deconditioning, must be defined. The technology base for support of humans for flights of several years does not exist.

KEY TECHNOLOGY AREAS AND OPPORTUNITIES

The committee identified nine key technology areas and opportunities.

1. Evaluation of the threat: The exposure of human space travelers to candidate missions must be defined more explicitly if its severity is to be evaluated. Flight duration, which has most profound effects upon the cardiovascular, immune, and musculoskeletal systems, must be spelled out along with the g-stresses and work requirements imposed by intermediate landing and exploration. The radiation dosage associated with various missions, beyond the protection of the Earth's magnetic field, especially the heavy ions, must be characterized as to their relative biological effect with sufficient accuracy to permit adequate shielding or other protective measures or treatment techniques to be designed. The problem of protection from solar flares should be solved by adequate warning and access to a "storm shelter."

2. Long-duration animal exposures: It is impractical to build toward long-duration human habitation in space solely by the incremental approach of successively longer trials with a small number of astronauts. The Soviet experience with long-duration manned flights has raised many questions, but has not provided definitive answers as to the practicality of multiyear missions. Just as is the case for other areas of human health and environmental medicine, animal models must be used for the major investigations of new and hazardous fields, to be followed by verification with human subjects. In the case of exposure to radiation loads, this practice is well developed and should be applicable to space flight with the possible complication of interactions between weightlessness and radiation effects. The direct influence of weightlessness, however, requires long-duration exposure of colonies of rats and monkeys to orbital flight. These tests must be carefully monitored and controlled to assess the physiological state of the animals at regular intervals and to assure that changes are not the results of other influences, such as atmospheric contaminants. For the controls, a 1-g animal centrifuge is absolutely necessary, and it too must be shown to provide an adequate control environment.

NASA's past animal experiment programs, designed to contribute to the man-in-space program, have been only marginally productive because of uneven funding and launch opportunities. Cooperative programs with the USSR on animal experiments and recent Spacelab results are beginning to show the relevance of basic measurements to human health in space. The technology initiative

the committee envisions in this area must be well funded, carefully controlled, and treated with the priority and seriousness it requires.

3. Incremental human exposures to weightlessness: In parallel with the long-duration animal experiments, a series of carefully controlled and monitored human exposure tests should be initiated. In continuation of the "doubling up" exposures begun with Skylab, and building on the experience of the Soviets where applicable, the experiments should involve periodic regular physiological evaluations, including simulated stresses of working under 1-g conditions. Successively longer exposures, following the long-duration animal tests, may require dedicated subjects whose primary role is to provide data on physical and psychological tolerance to weightlessness. Careful ground-based controls and adequate subjects for a meaningful statistical analysis are required to draw valid conclusions rather than relying on anecdotal evidence.

4. Countermeasures to deconditioning: A number of techniques have been suggested and some methods have been tried to prevent or slow the negative aspects of human adaptation to weightlessness that result in a deconditioned state for work in a 1-g environment following multimonth exposure to microgravity. It is essential to develop and test these candidate countermeasures in rigid controlled experiments using the animal and incremental exposure human evaluations described above. Exercise, for example, is a current favorite countermeasure. It is reported that the Soviet plans call for several hours per day of required exercise. Cosmonauts made use of a stretchable "penguin suit" to force work against a load with each limb movement. Astronauts on the Shuttle use a treadmill. However, the type and duration of exercise effective against the deterioration of bones, atrophy of muscles, and weakening of the cardiovascular system in weightlessness has not yet undergone the careful analysis and experimental verification they require.

Other types of potential countermeasures are in various states of research. The lower body negative pressure device, which causes a fluid shift toward the feet, has been used as a stressor and stimulus for counteracting deconditioning, but has not been evaluated adequately as a countermeasure. In the critical area of bone decalcification, a number of potential mechanical and electrical countermeasures have been proposed but not fully evaluated. To the extent that bed-rest facilities can provide the deconditioning environment,

many of these candidate countermeasures can be evaluated without initial access to space.

5. Specification for artificial gravity: If none of the simpler countermeasures prove adequate to counter the deconditioning associated with long-duration exposure to weightlessness sufficiently to permit work on the surface of Mars and to permit healthy readaptation to Earth's gravity, then serious consideration must be given to the provision of artificial gravity by a rotating spacecraft or pair of tethered vehicles. This concept entails considerable engineering complexity and has been put aside as unnecessary and undesirable in the past. However, the requirements of a Mars mission force reconsideration.

Currently, the important parameters defining the rotating craft (radius and angular velocity) are not based on any sound experimental results. For example, the minimum acceleration level required to prevent deconditioning for continuous exposure is not known; neither is the influence of a gravity gradient for spacecraft systems in which the human's height is a significant fraction of the radius. The maximum allowable rotation rate, presumably based upon the tolerable Coriolis forces during linear motion or the vestibular disturbances associated with head movements producing cross-coupled angular acceleration, has never been evaluated for subjects who have undergone the process of adaptation to weightlessness and enjoy a relative immunity to motion sickness. The NCOS recommended the development of a large Artificial Gravity Research Facility to study this question. A first step is the provision of facilities for the Space Station that will permit some of these questions to be approached using a large centrifuge.

6. Extravehicular activity: The vastly increased use of astronauts for construction, servicing, and repair of satellites in LEO will require a major evolution of their suits, tools, vehicles, and displays. The problem of excessive time for prebreathing to avoid the bends in the current 4 psi spacesuit is well known, and increased emphasis should be placed on the developments under way to produce a practical higher pressure suit. The major associated suit problem is the glove, which still presents an obstacle to easy use of hand tools or dexterous EVA operations. Appropriate tools for EVA work need further development and testing. Information transfer and displays to the astronaut during EVA also deserve increased attention. A reliable and dependable mobility aid, or space taxi, to assist the

astronaut in his local travels around what will become a larger and larger workplace is a desirable goal. Finally, a developmental effort is needed to provide new, free-flying robots and teleoperators so capable that human EVA is saved for special feats of judgment and dexterity.

7. Closed environmental life support systems: The development of new means of providing or recycling water, air, and food in space has usually lagged behind the definition of specific missions. Some current activity is in place in this area, but it deserves vastly increased support and integration into flight demonstration programs in order to provide the proven technology base for its use on long-duration nonresupply missions. Partial and full recycling of air and water and initial experiments with plant growth for food should be expanded. Provision for integrating these pilot plants into an experimental system for testing on the Space Station should be explored. In any event, life support system development must be considered as part of vehicle systems design. This important area is discussed further in chapter 7.

8. Human factors/man-machine interface: The presence of humans in future space programs is taken as a given—whether for long-duration flights or for extensive construction, servicing, and observation in LEO. The nature of human involvement, however, is broad and changes as the increased use of computers and robots frees crew members from many repetitive tasks. The nature of displays, use of sensors, high-level human management of robot tasks, and involvement of artificial intelligence for man-machine systems in space requires vastly increased research.

9. Psychological aspects of humans in space: There is a legitimate concern that the psychological stress of long-duration, small-crew missions may set a practical limitation to the duration of the mission. Neither multimonth terrestrial simulation, nor even Earth orbit missions are necessarily an adequate test bed because of the proximity to home and the possibility of reasonably fast return in the event of an emergency; however, they may provide preliminary psychological data. The relevant aspects of behavioral psychology that are of concern deal with crew selection, crew structure and training, and spacecraft habitability. Although this area is not usually considered a technology field, it does require attention to enable the successful completion of some of the more ambitious long-duration missions.

RECOMMENDATIONS

Before proceeding with any long-duration manned missions beyond Earth orbit the following issues must be addressed thoroughly and promptly.

- Microgravity effects on the human cardiovascular and musculoskeletal systems are barely understood beyond three months—and are unknown for multiyear missions. Human and animal long-duration experiments are required to assess the deconditioning and evaluate protective devices and protocols. Artificial gravity, as one countermeasure, needs experimental validation to establish g level, minimum radius, and maximum rotation rate.
- Radiation protection against solar and cosmic radiation, beyond that offered by LEO, requires threat evaluation and improved means of shielding or avoidance.
- Closed life support systems require development and extensive validation on Earth and in space to permit a practical, long-duration manned mission without resupply.
- EVA for construction, exploration, servicing, and repair will require significant advances in high-pressure suits, gloves, tools, and mobility aids.
- Humans will need to augment their intelligence and manipulative skills with automated, teleoperated, and robotic systems.
- Human factors, including crew selection and training, habitability, man-computer interface, and communications, represents another field for research essential to long-duration manned missions.

7
Life Support Systems

BACKGROUND

Life support systems for human crew members include maintenance of the environment, especially temperature, pressure, and atmospheric content; supply of food and liquids; provisions for personal hygiene; and waste collection and handling. In this section, environmental temperature and pressure supply are not considered since they are not limiting technologies.

Historically, NASA has led in the development of life support systems, and interest in these systems has basically paralleled the major manned space programs or the anticipation of a new manned space initiative. Mercury, Gemini, Apollo, and Skylab were the driver missions for supplying consumables from the ground and storing waste in the most practical manner, but none of these missions attempted to close the recovery/recycle loop.

Early in the Apollo program it was recognized that the crews' water supply must be sterilized even though it was produced by the reaction of hydrogen and oxygen in the fuel cells; bacteria growth in water storage tanks could not be controlled otherwise. Just as water districts that supply large cities use chlorine, so did Apollo. However, chlorine dissipates quickly and the vehicle's water supply had to be chlorinated on a daily basis. Crew reactions were

negative, since the water had a strong chlorine taste and the process required crew action. The lunar module (LM) was provided with water treated with iodine prior to liftoff, and crews preferred this over the chlorinated Apollo command module water.

Carbon dioxide ($C0_2$) and odor removal was accomplished with lithium hydroxide (LiOH) canisters, a practical method for a three-man crew and two-week mission.

Personnel hygiene facilities on Apollo were basic at best. Clean-up was accomplished by wetting cloths and disposing after use in a trash compartment. Waste liquid was pumped directly overboard as generated. Condensate was pumped to a waste tank for storage. A diaper-type device was used for fecal collection, and after use it was stored in a vented waste storage compartment.

STATUS

All food continues to be loaded at launch. To correct the potable water problem encountered on Apollo, development work was started on ways to sterilize the supply system without crew involvement. The result, presently installed on the Shuttle, is a canister charged with iodine-impregnated resin. This device is called a microbial check valve, because it checks or controls bacteria, not the flowing fluid. The unit has a limited life of three missions and treats only water generated on board the vehicle. Water serviced into the vehicle during ground turnaround is treated with iodine prior to loading. The iodine will plate out on the wall of the storage container, depleting the concentration and resulting in some bacteria in the water, but low enough in count to be acceptable.

Body waste handling continues to present many problems, although it has been improved and is now pumped into a waste tank and stored. The tank is dumped overboard through a heated nozzle if required. Defecate waste is now freeze dried. Recently a vane compactor has been added to increase capacity. $C0_2$ and odor are still removed by LiOH and charcoal scrubbers.

OPPORTUNITY

Longer duration missions will require significant improvement in life support systems. A crew of six requires 60 lbs of food, water, and oxygen per day and generates comparable figures in waste. In

addition, the crew requires 20 lbs of LiOH per day. Total waste including trash could be as high as 100 lbs per day.

The Space Station program will represent the first steps in advancing the state of the art for life support systems. The water loop will be nearly closed by recovery of potable, hygiene, and wash water. Candidate technologies for this recovery include phase change and filtration processes. The CO_2 loop will be closed by either electrochemical, absorption/desorption, or molecular sieve processes. Odor and trace contaminant control will still be handled by filtration. However, food will continue to be supplied from the ground, and no recycle of human waste is planned for the initial phases of the Space Station. Figure 8 illustrates a closed life support system.

Little work has been done on processing solid wastes other than compaction, stabilization (by drying or using a biocide), and storage for return to Earth. These approaches are not regenerative. Nothing is recovered from the waste material, not even water. This is one area that will require great technological strides for long-duration space missions. In order to reduce the quantity of waste material and begin to close the carbon loop, some form of waste oxidation must be used. One approach considered promising is supercritical water oxidation, i.e., the decomposition (reforming) and combustion of oxidizable material in aqueous suspension with oxygen at elevated temperature and pressure. With temperature and pressure maintained above the critical values for water, 374°C and 218 atm, respectively, work on the process to date indicates that it is capable of the rapid transformation of an aqueous slurry of waste organics into pure water, clean gas, and inert inorganic ash.

Separate life support subsystems that could potentially be improved by implementation of the supercritical water oxidation method include those for: trace contaminant control, CO_2 removal, and water recovery.

As the duration of future manned space missions increases, a logistics crossover point will be reached where it will become more economical to provide environmental control life support systems for the regeneration of needed elements from metabolic wastes and production of food in space than to incur the costs of resupply and stored consumables charged against payload. Extended-duration space activities will only be practical if spacecraft and crew members

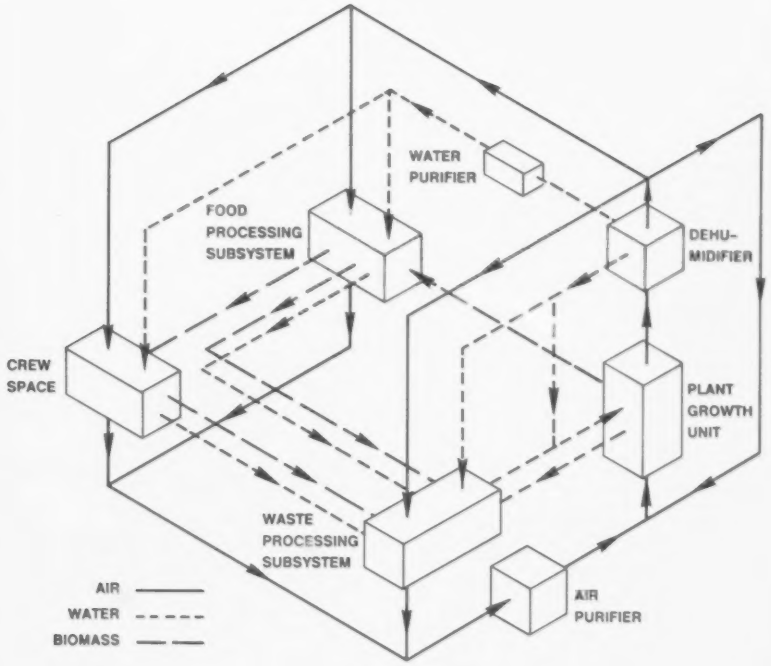

FIGURE 8 Schematic of Closed Environment Life Support System. *Courtesy of NASA.*

can function as a balanced ecological system. NASA-sponsored studies of this technology have referred to those systems as Closed Ecological Life Support Systems (CELSS).

CELSS functional requirements for space application will be to supply oxygen, water, and food for support of human life on a continuous basis while maintaining a balanced stable spacecraft ecology. The CELSS subsystem must satisfy both the environmental control, life support, and food production space vehicle functional requirements. While the choice of CELSS components will be highly space-mission dependent, it appears that CELSS will be biotechnical in composition, consisting of human, plant, and microorganisms integrated with certain other physiochemical components.

Long-duration Mars missions and Mars and lunar colonization will require that life support systems be closed and that extra-terrestrial resources be utilized.

Spacecraft CELSS math modeling is another area of opportunity, generally requiring development of computer simulation programs to predict performance during transient conditions due to: orbital cyclic light and dark operation (with variable heat rejection and power availability), cyclic adsorption bed operation for CO_2 removal, cabin pressure control, cabin temperature and humidity control, regenerative process subsystem operation (shut-down, start-up, controller actions), off-nominal operating conditions, anomalies, and so on.

Computer programs have been developed by NASA and the aerospace community to accomplish these transient simulations for individual subsystems, groups of subsystems, and complete systems. Existing thermal analyzer programs, such as SINDA, have been effectively used in some of the analyses.

CELSS analysis computer programs, capable of analyzing complete systems, generally are more demanding of users than are thermal analysis programs because of the wide diversity of the data required. In addition to thermal exchange simulations, these programs include simulations of chemical reactions, thermodynamic processes, mass transfer process, and balancing of pressure drop with head rise.

A general-purpose CELSS computer program on a level with SINDA or NASTRAN (NASA structural analysis) needs to be developed. Existing general purpose CELSS computer programs, such as the "G189" generalized CELSS program developed by the Johnson Spaceflight Center or the "CASE A" CELSS computer program under development at NASA/Ames, could serve as a starting place. The program needs to be user friendly, provide high user visibility, and be computationally efficient with respect to computer run time.

These system and development tool enhancements represent significant opportunities for Space Station growth. For long-duration manned missions beyond LEO where logistics supply is extremely costly or impractical, technology development of fully integrated closed-cycle life support systems will be enabling.

RECOMMENDATIONS

Considering the enabling nature of the technology for support of humans in space for long duration in and beyond LEO, NASA should proceed with research of completely closed life support systems. This effort must include the crew environment, water and waste recycling, and production of food. In addition, an increased effort on equipment technologies to improve personal hygiene procedures is appropriate.

Systems development tools also need emphasis to ensure that the technologies can be properly combined in future systems. Analysis and modeling tools must be advanced. Focus should also include simplicity in mechanization for low-cost maintainable systems.

Ground and flight demonstrations and life support systems validation should follow initial Space Station ground test efforts as the program moves to flight or operational status. The Space Station itself will represent an appropriate flight test bed for future systems.

8
Automation, Robotics, and Autonomous Systems

BACKGROUND

The time has come to add a new technology, automation and robotics, to the other major technologies—propulsion and power, materials, and information management—that are considered essential to U.S. capability to operate effectively in space. There are three reasons: affordability, achievability, and need.

There is an analogy between the evolution of space systems and military aircraft that may be helpful to cite. For a long period, the technologies considered critical to advancing the capability of military aircraft were propulsion, materials and structures, and aerodynamics. A time came when aircraft information and guidance and control systems became so central to success that their underlying technology took its place beside the other, traditional technologies. Today this capability has advanced to such concepts as the pilot's apprentice and total in-cockpit simulation. The pilot manages but the automation system flies the mission. A similar step change in the level of operations is in store for the space enterprise; but the magnitude of the step will be much larger.

Except for specific instances (e.g., deep-space missions and Shuttle flight path control), NASA's use of automation and robotics in space has been limited. The primary reason that spaceworthy

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robotic capability does not exist is due to lack of investment in the underlying technologies. The United States has managed to "get by" to date because

- For manned missions: (a) missions have been short and intense, allowing the use of large ground crews for mission control; and (b) astronauts have historically been "pilots" rather than in-space operators.
- For unmanned missions: (a) spacecraft have been considered "disposable" and were not designed to be serviced on orbit; and (b) Earth orbiting spacecraft are readily commanded from the ground because of easy communication (relative to deep-space missions).

Changes driving the need for automation and robotics in space include vast increases in mission duration objectives and complexity (e.g., most of the "easy" space science has been done); a major change in the primary role of astronauts to in-space workers (which will be intensified in the Space Station era); and the deployment of in-space serviceable assets.

STATUS

Future missions of NASA will rely increasingly on automation, robotics, and autonomous systems for the following reasons:

1. Safety of humans in space: Exposure of humans to hazardous environments such as EVA, nuclear and hazardous chemical fuels handling, and high-radiation zones should be minimized.
2. Increased human productivity: Routine and/or hazardous tasks can be automated, and crew time-consuming EVA preparation can be minimized by use of robots.
3. Performance of tasks that are infeasible for humans: Robots can greatly enhance human capabilities for such tasks as moving large structures, capturing spinning satellites, and controlling complex systems.
4. Enabling new missions to other planets: Mobility and manipulation aids for manned missions and automated systems for complex unmanned missions, e.g., Mars rover/sample return, will provide new capabilities.

The cost of maintaining humans in space is extremely high, even in LEO; therefore, each human must be supported by systems that

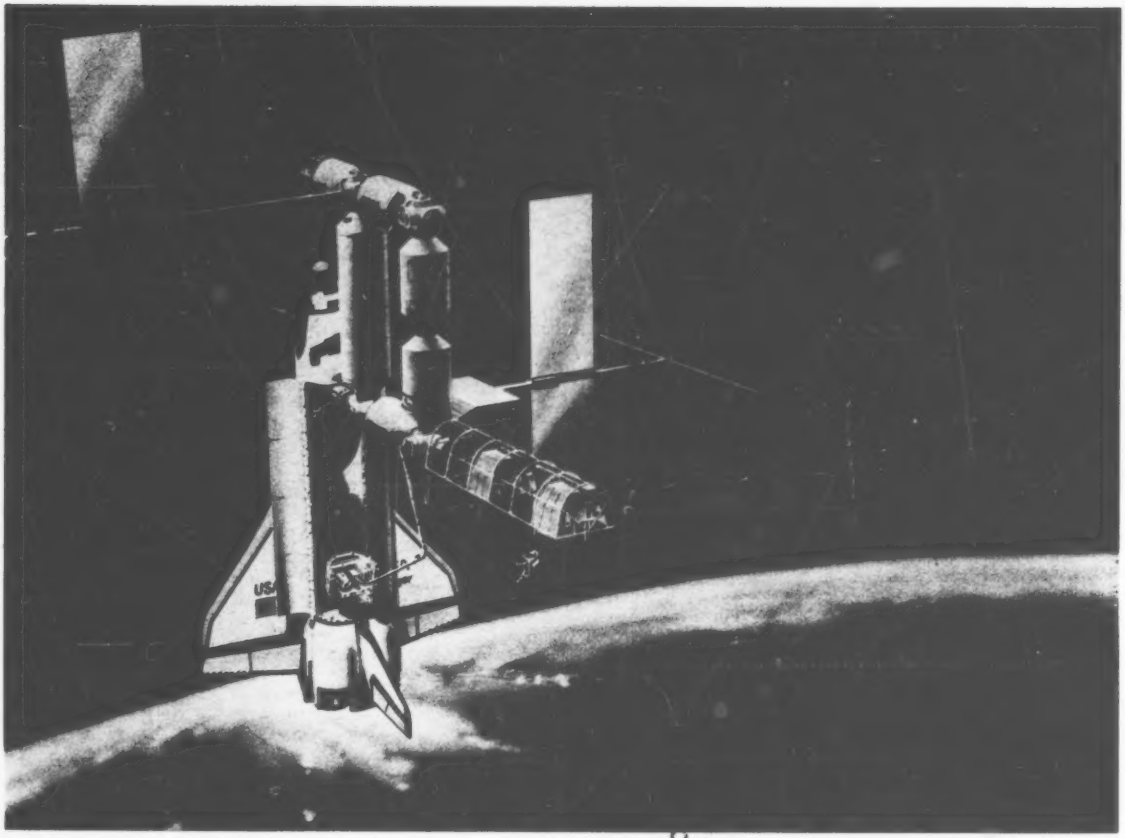

FIGURE 9 Surrogate space robot at work: an interim measure.

can enhance astronaut effectiveness to the utmost. Each human must be free of mundane and repetitious tasks—of mind or hand—so that the unique judgment and dexterity that only humans possess are optimized. All other tasks should be carried out by machines.

Human EVA is extremely expensive, involving extensive preparation time and monitoring by other humans, in addition to costly equipment and procedures. In the future, this can usually be a task for free-flying robots; and in microgravity they can have some remarkable capabilities. They can be light, limber, and dexterous. They can travel and maneuver. They can be any size, including quite large. And they can operate effectively in teams.

Such machines could be part of U.S. space systems beginning about the year 2000, but only if the technological base for them is developed in a timely and sustained way. It is true that some of the technology required for space automation will be developed independently of the space program—especially computers of greater and greater capacity (with less and less volume and power required). But other critical aspects are space peculiar, and will not be available unless they are pursued vigorously by NASA itself. Two examples are the human/machine interface and free-flying robots in microgravity. Such robots will be so fundamentally different from those that will evolve in the Earth-bound environment that they will never be available if NASA does not develop their underlying technologies (e.g., control of flexible lightweight manipulators, and maneuvering and manipulating at microgravity). The cost and waste of human EVA time will constrain space operations to a small fraction of what could be.

Ongoing programs include research and development for Earth-application automation and robotics, e.g., within the DARPA, SDIO, the National Science Foundation, and industrial robotics and teleoperation programs. The current support of space automation and robotics R&D is almost entirely NASA funded (at a level of about $25 million a year starting in FY 1988).

An exception to this is the technology of mobility and autonomous navigation that could be applied to a planetary rover. This technology is currently supported primarily by the DARPA Autonomous Land Vehicle (ALV) program and some Army programs.

FIGURE 10 Current space robot concept; orbital maneuvering vehicle with manipulative capability.

In 1985 the Automation and Robotics (A&R) Panel, with non-NASA specialists in automation across the spectrum of the space-relevant technologies, was commissioned. The panel addressed the question of which automation and robotics technologies were critical for NASA to support (and which would not require NASA support) in order for space operations—and specifically, operations of the Space Station—to advance to the new high level that only automation can make possible. Attention was given to timing and evolution, and to selected space demonstrations, as well as to the sequence of primary technology-base achievements that would be necessary for fully-automated, minimium-cost, high-capability operation of the Space Station by the year 2010. Drawing upon experience with similar DARPA programs, the A&R Panel recommended that the cost of the necessary national technology development program should be between $100 million and $190 million in 1990.

KEY TECHNOLOGY AREAS AND OPPORTUNITIES

Some of the technology required for space automation and autonomous systems will be developed independently of the space program, and NASA should certainly take advantage of these developments. But other critical aspects, such as human-machine interface and free-flying robots in microgravity, are space peculiar, and will not be available unless they are pursued vigorously by NASA itself.

The microgravity and space exposure environment dictates special design and protection considerations for automated and robotic space systems, as opposed to terrestrial systems. Long transmission delays and limited or absent crew in space imply higher levels of supervisory control and local automation. The requirements for flexible operation in the performance of unspecified tasks in an uncertain environment stand in contrast to the repetitive tasks of industrial robots, for example, and place special demands on validation.

Thus, although considerable research, development, and use of automation and robotics technologies are in place for terrestrial applications, space applications pose unique requirements to which the NASA program must be directed. These include the following:

1. Design will be driven by low-mass requirements that limit power, size, and communication bandwidth (in the case of robotics,

mass limitations require mechanization of light, limber manipulators interacting with dynamically active elements such as structures, transportation elements, and free-flying satellites).

2. Multipurpose robots will be required for operation in the complex, uncertain, hazardous space environment (relative to factory robots that tend to perform limited, well-defined, repetitive functions) because launching a wide variety of special-purpose robots is too costly and may result in single-point failures, and many space tasks are not predeterminable, thus flexibility and adaptability are essential.

3. Very high reliability and safety requirements (especially in manned systems) place special requirements on the validation of intelligent systems.

4. Advanced sensing and manipulation/control techniques will be needed for the space environment.

5. This, in turn, will require advanced information processing of a variety of data types; this processing will require the use of AI to achieve a high degree of autonomous capability.

6. AI techniques must be specially selected for the requirements and constraints of space missions.

7. Most important, the man-machine interface is especially critical in manned space missions where each crew member will perform a variety of functions requiring interaction with automated and robotic systems.

There is lively speculation about how humans can most effectively interact with machines in space—with the "thinking" experimental systems that will assist in mission management and scientific discovery as well as with "doing" robots. Command at the most sophisticated level is the goal. Extensive research will be needed to develop a system for interaction between humans in space and the autonomous systems that serve them, and no one but the space community will develop it.

Key technology areas that need to be addressed include:

- rapid, precise control of flexible, lightweight manipulator systems;
- cooperation between manipulators and between robots;
- mobility and maneuverability;
- telepresence: human interaction and effective displays;

- trainable, model-based systems to be used in unknown environments;
- real-time expert systems and predictors;
- tools and effectors;
- sensing and perception;
- advanced in-space computing systems; and
- maintainability.

RECOMMENDATIONS

An aggressive space automation and robotics program will benefit both manned and unmanned missions by allowing increased human productivity both in space and on the ground, increasing science or commercial return on investment, reducing operations costs, improving safety and comfort of space operations, and enabling numerous space achievements and operations otherwise not realizable.

Increases in funding in this area should be directed toward both basic advances in the key enabling technologies and applied research focused on the special needs of space automation and robotics. "Demonstration" activities should focus on: (1) technology integration into automated and robotic systems (because there are considerable technological issues in such systems integration), and (2) validation of the utility, reliability, safety, and so on of automation and robotics technologies in space applications.

The university community, with its basic research orientation, is ideally suited to play a major R&D role in automation and robotics. The field is complex, and many different approaches need to be tried. Also, the technologies under discussion have a wide variety of applications and can be implemented at many levels of complexity and system integration. Ultimately, however, NASA will have the responsibility to provide facilities for integration and validation of autonomous space systems.

9
Power

BACKGROUND

Power supplies for space systems comprise an enabling technology base. The availability of long-lived (7 to 10 year), reliable (99+ percent), radiation-resistant power supplies has been a cornerstone of the world space exploration program. Since the beginning of the U.S. space program, solar power and long-lived lightweight battery systems have had relatively continuous R&D support. The technologies are maturing but major performance enhancements are still sought in mass, volume, survivability, safety, and reliability.

For either DOD or NASA missions requiring independence from sunlight and enhanced resistance to cosmic radiation, the nation has supported the development and launch of radioisotope thermoelectric generators (RTGs). In fact, 38 nuclear-powered systems[1] were successfully flown on 23 DOD and NASA missions. The success of the RTG launches and missions and the importance of the scientific and military information derived from missions requiring RTG power supplies will likely lead the United States to continue to develop and launch RTG power supplies. These energy systems are related to spacecraft developed to support unique mission needs—RTGs were tailored to optimize the attainment of the mission objectives.

However, as the energy requirements for both scientific and military missions increase and commercial mission requirements develop there will be an increasing need for larger, more utility-like energy systems. Figure 11 compares the NASA missions between 1965 and the year 2005. DOD classified missions show comparable trends. Providing energy of these magnitudes for NASA and DOD beyond the year 2000 will require major technology development of all power supply options—photovoltaic, solar dynamic, and nuclear; however, only nuclear reactor generated power can meet the very high energy requirements.[2] This has long been recognized by NASA, the U.S. Department of Energy (DOE), and the DOD.

Nonetheless, the nation has only launched and operated one nuclear reactor power supply, the SNAP 10A system referred to in Table 2. SNAP 10A provided 500 watts of electricity, operating successfully for 43 days on orbit when a relay failed, triggering safe, permanent shutdown of the reactor. As noted earlier, the entire space nuclear power program in the United States was terminated in 1973 due to budgetary pressures and as a result of the absence of hard "missions" for either DOD or NASA. Thus, a very substantial national investment over a 20-year period has yet to be capitalized on by the U.S. space program.

Recognizing the adverse future impacts of this situation, the government reinitiated a space nuclear power development program in 1983. The SP-100 program was initiated to develop a reactor flight system that could provide between 10 kW and 1 MWe in the 1990s; the SDIO plans to support a flight demonstration of the SP-100, powering a nuclear-electric propulsion system in this time frame. The SP-100 program is now entering a $560 million, five-year ground engineering development phase preceding this flight qualification test.

Because safety and environmental impact will be central policy issues prior to any flight program approval, a NASA/SDIO/U.S. Department of Energy (DOE) safety policy statement[3] has been formalized in a three-party agreement. It will be necessary to demonstrate successful implementation of the safety policy prior to flight. The policy calls for both design features and launch, operation, and end-of-life disposal procedures that will assure public safety and lead to minimal environmental impact.

For example, the reactor will be launched in a frozen, unoperated state so that launch abort accidents that could threaten system

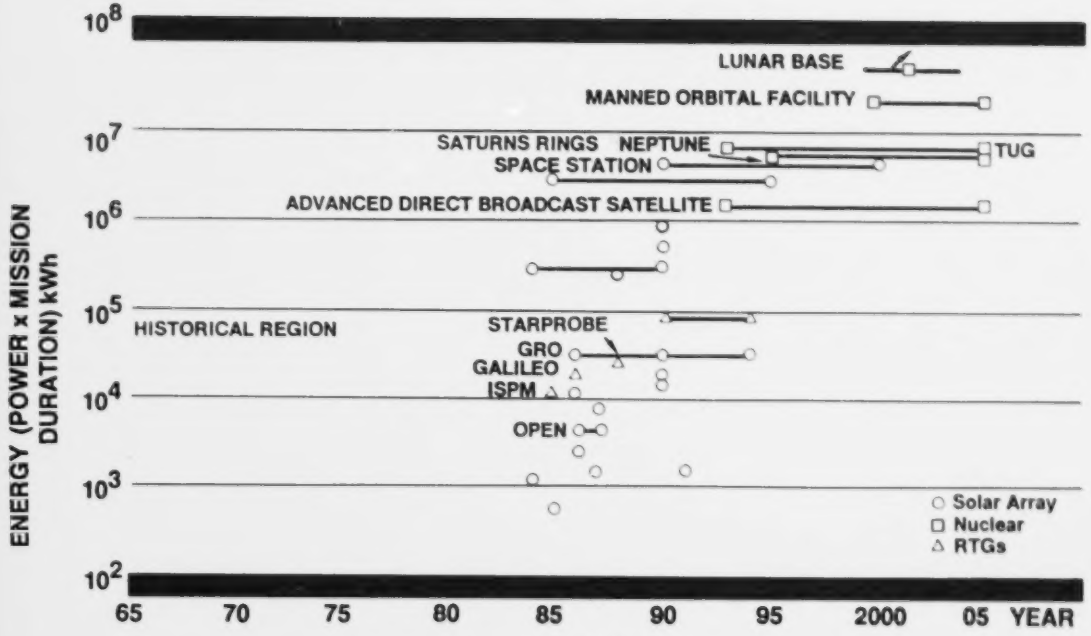

FIGURE 11 Future space energy demands and appropriate sources.

integrity pose no threat of radioactive release to the environment. Additionally, the system will only be operated in high-orbit configurations so that the fission product inventory can decay, following shutdown, to levels that would not unduly expose the world population to radiation, even in the event of an unplanned reentry of the reactor. For additional safety, the system is designed to re-enter intact. These and other defense-in-depth safety philosophies are designed to place the highest priority on public health and safety.

In FY 1986, DOE and the SDIO initiated a Multimegawatt Power Supply program for SDIO missions. This program has minimal NASA involvement at this time. The program goals are to evaluate power supply options and develop technologies for power supplies in the one to several hundred megawatt steady-state and pulsed power range. The program is oriented toward a 1991 decision on whether nuclear reactor and/or other power supplies are technically feasible and on selection of power supply and reactor design options that should be carried forward in a ground demonstration phase. Multimegawatt power supplies are not envisioned to be available until at least the year 2000.

STATUS

The NASA R&D budget continues to support technology development and enhancement of photovoltaic, solar dynamic, and battery power supplies for NASA's near-term missions (e.g., unique spacecraft for planetary exploration, scientific investigations, Earth resource evaluations, and a near-term Space Station), and these are important efforts. Continued R&D holds promise to increase the specific power of thermoelectric systems by factors of 3 to 5. R&D directed toward advanced solar dynamics is expected to yield a lower mass, reduced drag power supply for the Space Station, up to 300 kW.

The NASA R&T effort for larger utility-like energy systems includes advanced solar photovoltaic and dynamic systems and participation in the SP-100 program. The NASA contribution to the SP-100 program has remained level at $4 million to $5 million per year (the FY 1987 total budget for SP-100 is approximately $70 million per year). NASA provides the SP-100 program with advanced technology development and support to the nonnuclear systems effort. A Stirling engine is under development that could double

specific power. For the Multimegawatt program, NASA contributes no funding, but supplies technical support from the NASA Lewis Research Center.

Table 3 describes the present status of space nuclear power applications for the military. The table shows that there are many potential missions, technology options, sponsors, and flight readiness goals over a very wide power range. Because NASA has recognized its future energy demand requirements (Figure 11), it is presently planning to increase its R&D investment in future years for nuclear power development. Missions that may utilize nuclear power include manned and unmanned Mars missions,* a lunar base, a Mars base, outer planetary missions, and OTVs. NASA is presently reviewing the mix of missions for which nuclear power systems are required. The nation's investment in space nuclear reactor power systems and isotope power technology could be as high as $1 billion to $2 billion between now and the year 2000.

OPPORTUNITIES

NASA's investments in photovoltaic, solar dynamic, and Stirling engine development have the potential to meet and/or enhance near-term spacecraft mission needs. The work is technically sound and should be strengthened to match national mission needs. NASA work in high temperature superconductivity also has important potential application to space power. For a wide range of spacecraft serving scientific, military, and commercial needs, integration of advanced power subsystems with parallel advances in other subsystems of the spacecraft bus (e.g., propulsion system, thermal management, structure) can lead to a 30 percent reduction in bus mass—more for some mission classes. This can double the payload mass allowed in most cases. Similar considerations apply for lunar and planetary rovers.

DOD requirements are likely to drive the development of nuclear power systems in the near term. NASA can leverage these development funds effectively and meet future mission needs by increasing R&D support to develop nuclear power supplies that are optimal for NASA missions. Merely depending upon the DOD-developed power supplies may not meet this need. With a modest

*The Mars rover has special needs for a low-mass, high-energy power supply.

TABLE 3 U.S. Space Power Program--Military Applications

Power Range	Example Potential "Missions"	Power Technology Options	Existing Programs (Sponsors)	Approximate Target IOC	Characteristic System Operating Time	Technical Risk
1 - 5 kWe	DSP, BSTS, Mars Rover	Solar, Nuclear, DIPS	DSP (USAF)	1995+	7-10 yr	Low
5 - 50 kWe	SLC, SBR, Station Keeping	Solar, Nuclear	SLC (USN)	2000	7-10 yr	Low
20 kWe - 1 MWe	SBR, NEP, Station Keeping	Nuclear	SP-100 (SDI, DOE, NASA)	1992+	7-10 yr	Moderate
0.5 MWe - 10 MWe	SBR, NEP, Station Keeping	Nuclear	TFE Verification (SDI)	2000+	7-10 yr	High
10 MWe - 100 MWe	NPB Discrimination	Nuclear, Chemical	None	2000+	1000-3000 s	High
100 MWe - 500 MWe	SDI Prime Power	Chemical, Nuclear, Storage Systems	Multimegawatt (SDI, DOE)	2000+	1000-3000 s	Very High
200 MWt - 4000 MWt	DNP, Manned Mars	Nuclear	AF Forecast II (USAF)	2000	1-3 h	Moderate

Acronyms

DSP	Defense Support Program
BSTS	Boost Phase Surveillance and Tracking System
SLC	Submarine Laser Communication
SBR	Space Based Radar (unspecified type)
DNP	Direct Nuclear Propulsion
DIPS	Dynamic Isotope Power System
TFE	Thermionic Fuel Element
NEP	Nuclear Electric Propulsion
SDI	Strategic Defense Initiative
NPB	Neutral Partical Beam

increase in funding, NASA will have a stronger impact on the power supply systems that are developed. By expanding its involvement in the SP-100 and Multimegawatt programs, NASA can better serve its long-term mission critical needs.

In the low-power (1 to 5 kW) spacecraft area, the needs of NASA and DOD may overlap. A collaborative development opportunity for technologically common nuclear systems needs to be investigated. For NASA, this need could become significant if the use of RTG-powered systems becomes restricted.

Because the lead time for nuclear power system development is long, NASA needs to get involved now for continuity, leverage, and mission-enabling technology development.

The payoff for NASA in maintaining adequate support for photovoltaic, solar dynamic, and Stirling engine and other power conversion development as well as in increasing funding and focus for nuclear reactor power system R&D can be expressed both in terms of mission enhancement or enablement and long-term cost savings. For example, planners of early lunar and Mars bases contemplate use of the SP-100 system on small outposts performing largely scientific and life support functions. Most studies indicate that as such outposts evolve, megawatts of power will be required.

Highly reliable, relatively lightweight nuclear power supply systems can enhance both the economics and the safety of such colonies. The outer planetary missions can be conducted in reasonable lengths of time only if SP-100-driven electric propulsion is available. While many other examples comparable to these could be cited, it is clear that the successful deployment of compact, high-power, long-lived reliable nuclear power systems is key to a viable and affordable national space exploration and utilization program.

ALTERNATIVES

Alternatives to the development of fissile nuclear power systems certainly exist. The United States can continue to utilize solar power systems, batteries, and RTGs. It is safe to say that the nation will do so with or without the development of nuclear reactors. Other more advanced, higher-risk technologies might also be possible, although some other concepts that have been proposed, such as antiproton annihilation and controlled fusion, appear either physically unreasonable or impractical in an engineering sense. For

high-power levels, fissile systems have considerable advantages. Solar arrays can be configured to increase in size beyond that now possible. As large structure technology comes to fruition, such arrays may become practicable.

Nonetheless, as power requirements grow, solar arrays become very costly to launch due to the unavoidable low-energy density associated with solar radiation; the mass of the solar array becomes too large and launch costs too great. Comparable arguments can be made for delivering high power from solar dynamic systems, batteries, and fuel cells.

If NASA takes no action at this time, it will lead to a situation in which, when high-power requirements arise, NASA will have to find a way to utilize nuclear-powered systems developed by the DOD. By becoming more involved in current programs, NASA can help assure the availability of appropriate power supplies for long-term and more aggressive civil missions. If it is determined at a later date that nuclear power systems different from those developed by DOD are required and if development programs are not initiated until that time, NASA will encounter a 10 to 15 year delay while technology is developed.

RECOMMENDATIONS

It is recommended that NASA continue to strengthen its solar power technology and Stirling engine development programs. It should build an integrated approach to improving the spacecraft bus for a wide range of mission needs. This also should include meeting lunar and planetary rover requirements. NASA should expand the scope and magnitude of its nuclear power development program. Specifically, NASA should become a stronger resource contributor to the total SP-100 program, expanding its effort now limited to conversion system technologies. It should, in fact, become a full partner in SP-100, applying more of its resources to the mainstream of the program.

Further, NASA should review its more stressing missions by defining requirements and evaluating power system options against the specific requirements. Optimal combinations of power sources should be defined and R&D programs initiated on a time frame

appropriate with anticipated mission scenarios. For the nuclear reactor power system option in particular, it is important to introduce it neither too soon nor too late in this long-term scenario.

One of the lessons learned from past U.S. space reactor development programs is that the nation can inadvertently start development programs too soon, only to expend large sums of money with virtually no payoff for its high-priority missions. At the other end of the spectrum, it can be very cost-ineffective and technologically suboptimal to start a development program too late, only to have to conduct a crash R&D program with the concomitant waste of funds and associated increase in technical risk.

Much to be preferred is an orderly, properly paced, goal-oriented R&D program. This program should be coordinated and made complementary to all of the existing programs and sponsors shown in Table 3. In short, a national space nuclear power program is needed where NASA, SDIO, DOE, the Armed Services, and other users coordinate their activities, combine their respective funds, and capitalize on the potential common requirements among missions that have comparable goals and needs.

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10
Materials and Structures

BACKGROUND

Aerospace structures have been made of aluminum alloys for more than 50 years. Gradual development of these materials has provided improved strength, corrosion resistance, and formability, and has resulted in increasingly efficient and reliable structures. As elevated temperature requirements developed, titanium and steel alloys have been used in some applications.

Reentry vehicles and high-speed aerodynamic vehicles require enhanced thermal protection. Early spacecraft used ablators and insulated metallic heat shields and lighter-weight, reusable ceramic insulation was used for the Space Shuttle. However, major structures and materials breakthroughs were neither required nor employed in the transition from Apollo to Shuttle. Conventional (circa 1970) airframe materials technology coupled with minor improvements in metallic alloys, plastics, composites, and high-temperature, high-purity ceramics are still the mainstay of space structure design, with existing materials pushed closer to their theoretical limits. Improved production and processing methodologies have allowed expanded utilization of materials, and the designer's inventory of "space-rated materials" has increased.

STATUS

Substantial progress has been made in the past five to ten years in improving material performance, most prominently in the development of organic and metal matrix composites and in lightweight, stiff, aluminum-lithium alloys and high-temperature aluminum alloys.

Recently, the light weight and high stiffness of advanced composites have led to their use in the secondary structures of aircraft and spacecraft. As supportability problems have been resolved, these organic materials are finding application in primary structures, such as solid rocket motor cases, light aircraft, and high-performance military aircraft.

Structures now being proposed for large space stations and planetary vehicles pose some new material requirements, such as dimensional stability, low thermal expansion, and high stiffness. Directional composites can meet these requirements, but their satisfactory performance in the space environment over years of service has yet to be established. Materials used on space vehicles that have been recovered by the Space Shuttle show serious degradation in properties and appearance. Figure 12 summarizes the material characteristics required for space structures.

Efforts to predict damping in large, flexible space structures have not been entirely successful to date, and control of large space structures is expected to be a pacing technology in the exploitation of space.

Heavy-lift capabilities at much lower costs will be required to achieve space operations and exploration goals mentioned by the NCOS. Propulsion technology has always been a pacing item and long lead time and major investments are needed. Assuming no major breakthroughs or increases in Isp with chemical propulsion, however, mass fraction to orbit can only be increased by progress in structures and materials to reduce inert weight. To make this possible, a number of high-priority materials and structures technology needs must be pursued.

OPPORTUNITIES

Since great leverage for launch performance can be obtained by reducing the inert weight of tanks, airframe, the thermal protection system, and other components, new materials with very high

STRUCTURAL REQUIREMENT	MATERIAL CHARACTERISTICS
MINIMUM WEIGHT	HIGH MODULUS
	LOW DENSITY
	THIN PLY
DIMENSIONAL STABILITY	LOW THERMAL EXPANSION
	HIGH THERMAL CONDUCTIVITY
	MINIMUM HYSTERESIS
HIGH DAMPING	HIGH LOSS MATERIAL
NO CONTAMINATION	NO OUTGASSING
SPACE CONSTRUCTION	FABRICABILITY
	EASE OF FASTENING
MINIMAL SPACE CHARGING	GOOD ELECTRICAL CONDUCTIVITY

FIGURE 12 Summary of structural requirements for materials.

strength-to-weight ratios at elevated temperatures are required. Thus, aluminum tankage and structure might be replaced with composite and metal matrix materials. Separate heat-insulating thermal protection layers could be replaced with heat rejection via radiation by allowing the skin to get very hot, and perhaps by providing substructure active cooling. Advances in these technologies, which should be feasible by the early 1990s, have the potential of reducing the vehicle dry weight dramatically, compared to designs for the same payload weight using Shuttle technology.

Thus, materials and structures technology needs encompass space durable, dimensionally stable materials; advanced thermal protection system (TPS) concepts; advanced coatings; stiff, lightweight, high-strength, structural composites; advanced space structural concepts; and the development of an adequate data base for advanced concepts that will allow for confident design.

Metal-Matrix Composites

Advanced metallic materials, via alloy synthesis, offer the greatest potential for dramatically increasing payload to orbit. Higher strength and temperature resistant aluminum airframe products, using improved powder metals (PM) technologies, could yield corrosion-resistant, structural aluminum alloys to operate at temperatures approaching 900°F. Low-density aluminum alloys (specifically aluminum-lithium) can increase the modulus-to-density ratio by nearly 30 percent.

Metal-matrix composites offer advantages for large space structures, beyond improved gross liftoff weight, by virtue of tailored dimensional stability and non-outgassing characteristics. Advances in the various forms of graphite/aluminum, graphite/magnesium, and in rapid solidification technologies (RST) can be applied to deployable antennae, optical support structures, and large platforms.

Titanium-based material systems potentially could replace heavier nickel-based superalloys for temperatures up to 1,800°F through use of powder metallurgy and RST.

Advanced aerospace propulsion materials will require progress in oxide-dispersion-strengthened metal matrix composites, high-temperature titaniums to accommodate oxygen embrittlement issues, improved fatigue and fracture characteristics of titanium aluminides, and other emerging intermetallic materials.

Improvements in nondestructive inspection of advanced metallic materials must parallel product development. Otherwise, the improvements cannot be realized without sacrificing maintainability and reliability.

Metal-matrix composites are at an earlier stage of development than organic-matrix composites and processes used to make metal composites are more complex. Cost is a barrier. However, metal-matrix composites offer superior high-temperature properties, low coefficient of thermal expansion, dimensional stability, and tailored physical and mechanical properties. A well-defined research program should cover titanium, aluminum, and magnesium-matrix materials; a study of joining techniques and methods of increasing strain to failure and fracture toughness; and development of automated processing for cost reduction. For advanced high-temperature systems, fiber matrix interaction may require barrier coatings. Both the Aerospace Plane and a replacement Shuttle vehicle will require these major materials advances to accomplish

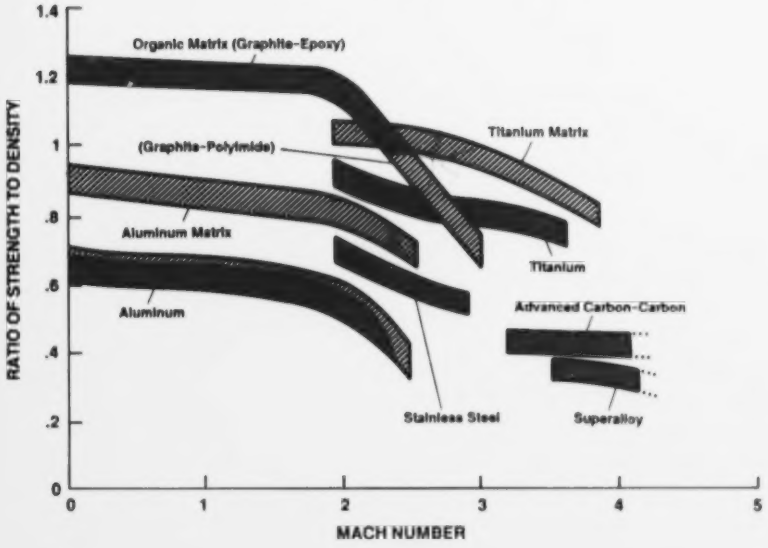

FIGURE 13 Strength of advanced materials as a function of speed. The shaded parts of the bars represent materials now in use, the striped parts materials under development. For aluminum the striped areas represent alloys that remain strong at high temperatures.

their intended missions. Figure 13 shows the strength of advanced materials at the increased temperatures associated with increased speeds.

Nonmetallic Structural Materials

Development of improved performance resins will dramatically increase the utility and applicability of composites on advanced space structures. Development and characterization of new high-temperature polymers will also be required.

Strong, stiff, lightweight fiber-reinforced thermosetting matrix resin composites offer tremendous payoff for structures while thermoplastic resin systems exhibit improved processibility and damage tolerance. Also, new ultra-high strength graphite fibers are becoming available for use in ultralightweight structures.

Understanding and control of outgassing of resins in space will

enable utilization of the lightweight, dimensionally stable resin-matrix composites in space structures where contamination control is critical for the operation of sensors and optical surfaces. Further, understanding the effects of long-duration space environment exposure on the structural and physical properties of the resin-matrix composites is essential to the selection and use of these materials.

As with structural metallics, the nondestructive testing (NDT) of nonmetal structural material will require advances in polymer chemistry and processing quality control. Unfortunately, some approaches to achieving improved composite matrix toughness could contribute to a higher coefficient of thermal expansion (CTE) mismatch between matrix and reinforcement.

A R&D strategy is needed to ensure that the technology will be available at the proper time for application to vehicle programs under development. An organic-matrix program should include:

- material advances aimed toward greater toughness, greater strain capability, higher temperature tolerance, increased compressive strength, and reduced costs;
- composite automated part manufacturing to lower finished structural costs;
- material consistency and standardization;
- development of a materials properties data base for space structures applications; and
- development of design methodologies unique to spacecraft structural requirements for composite materials to be applied to launch vehicles.

These thrusts should overcome the inhibiting factors that prevent more aggressive application of composites technology. The inhibiting factors include:

- poor understanding of fracture and failure modes as well as the behavior of composite structures under cyclic loads and the stress, temperature loads, and radiation environment of space;
- a smaller data base than for metals;
- concern over reliability of both mechanically fastened joints and bonded joints, as well as sandwich structure;
- the lack of verified methodologies that permit design with confidence for fracture prevention and durability, including thermoelastic analysis;

- manufacturing costs; and
- understanding and controlling outgassing of resin systems and the effects of the space environment exposure on long-term properties of resin materials.

Thermal Protection Materials

More cost-effective and weight-effective means of countering reentry heating in space vehicles and in aerobraking and aero-assist techniques are needed. Aerodynamic vehicle shell structures that provide structural as well as thermal performance and reusability should be a major thrust in an expanded space R&T program. Prime candidates are carbon-carbon composite structures, reinforced structural ceramics, new, lightweight titanium and nickel-aluminide compounds, and both titanium- and nickel-base alloy foil structures, sandwiched with insulation. Radiation-cooled vehicle structures rather than externally insulated structures should be the goal. The idea of a warm/hot structure is to provide a more cost-effective means of countering reentry heating than is presently afforded by the TPS, dominated by tiles, on the current Shuttle Orbiter.

Carbon-carbon concepts capable of providing structural as well as thermal performance, at temperatures probably as high as 5,000°F, merit special attention. The baseline system can be taken as the rayon-precursor, carbon-fiber reinforced, carbon-matrix system produced by pyrolysis/reimpregnation and utilized on the STS Orbiter leading edge.

The areas for improvement of carbon-carbon include new reinforcement fibers such as carbon, graphite, and other oxidation-resistant materials; new matrix materials and processing methods; and systems cost and fabrication cycle reduction.

Structural ceramics also deserve increased attention as thermal protection materials. Recent studies have identified means for producing reinforced, more-detailed ceramic structures by use of fibers or transformation toughening.

Advanced propulsion systems will use cryogenic fuels resulting in very cold internal temperatures. In the past, hot and cold structures have been addressed independently and thermal protection from extremely high temperatures involved a separate TPS. The Space Shuttle is built with this concept. Future concepts must

involve integrated hot/cold thermal protection systems that may incorporate active cooling. Some of this is under way at NASA and in other government programs. The key, however, will be to provide very durable systems that are lightweight and affordable. This will require a layered construction that can transition from the effects of one temperature extreme to the other. These structures must account for differences in thermal expansion, brittleness at low temperatures, and creep (in metals) at high temperatures. The use of separate TPS will still be necessary in some cases, but these may be supplemented by active cooling or may be designed for multiple use, though not as reusable as the vehicle. Adequate testing capability is essential if advanced thermal structures are to be developed.

Nonstructural Materials

A host of space-durable fluids, lubricants, seals, and coatings will be required for advanced s cecraft to meet the demands of extended missions in Earth orbit or to the Moon and planets. A new generation of nonstructural materials that are durable, maintainable, and fully serviceable in space as well as methodologies to use them must be identified to evaluate the space environment effects on these materials. Needed are:

- radiation-hardened components, instruments, and semiconductor computer elements that can operate for long periods of time in the hostile environments of the magnetospheres of Jupiter and Saturn;
- new thermal control coatings or films, or tailoring the structure of existing materials, that will be resistant to space environment;
- low-temperature materials technology for systems and instrumentation to operate on Titan or in colder environments of the worlds beyond Saturn;
- higher temperature technology for atmospheres of the giant planets and surfaces of Mercury, Venus, and Io;
- methodologies for simulated accelerated space-environment life-testing of materials intended for long durations in space; with attendant understanding of degradation mechanisms from combined radiation sources;

- understanding, prediction, and prevention of damage potential by space debris at LEO and GEO through analysis and prediction; and
- materials, processes, and methodologies for repair, refurbishment, and maintenance of materials and surfaces in space.

State-of-the-art thermal control coatings are products of the 1960s and are not adequate for the challenges to the next century. Space-stable, flexible, durable, noncontaminating, and space-functional thermal control materials are required.

STRUCTURES AND CONTROLS

Structures technology is one of the key pacing areas for the exploitation of space. Future flight vehicles, spacecraft, and platforms must be as light as possible yet strong and durable enough to withstand long-term exposure to space, the harsh environments of extraterrestrial surfaces, and repeated atmospheric reentry.

Large space structures technology is currently driven by the requirements for the Space Station and is focused on erectable truss structures. After the initial operation of the Space Station, the need will continue to develop for more complex structures in the form of planar structures (e.g., two-dimensional truss structures) and structures for large enclosed volumes. With increasing size and complexity, construction concepts will involve combined erectable and deployable systems utilizing manned EVA and robotic activities. Concurrent to these needs will be attachment and joining concepts to provide for growth and variation in design and at the same time provide for tight connections. Joints are presently the primary source of inherent damping in the structure. Damping will continue to be a concern in large space structures; however, more attention is needed to focus specifically on designing predictable and controllable amounts of damping into the structure.

Up to now, attempts to predict damping in large flexible space structures have not been very successful. The Solar Array Flight Experiment (SAFE) conducted on a deployable solar array from the Shuttle bay found the actual damping to be higher than expected. While this may seem encouraging, the source of this difference was in not fully understanding the dynamics of the system. This can just as easily lead to under prediction as over prediction.

Control of flexible structures is an area currently being addressed in a program to ground and flight test a deployable truss-beam. This is the first step toward developing methods to control both the shape and vibratory motion of space structures. In this context, the traditionally separate disciplines of structures and controls must be unified for the purpose of developing integrated methods and approaches for controlling and maintaining the desired shape and dynamic performance of flexible space structures.

The concept of control structure interaction (CSI) is not new to technology, but it needs to be more actively pursued in the area of space structures. To achieve this will require interdisciplinary teams. Also, concepts such as adaptively controlled structures should be developed in which the structure can be internally adjusted on demand to modify shape, damping, or stiffness characteristics. The structure would become part of the overall control system and the control system part of the structure.

A new area of structural activity is in precision structures such as those required for large optical instruments and antennae. These structures have many of the same characteristics of general large space structures (i.e., erectable/deployable, lightweight, and flexible). However, the overriding requirement is for extreme on-orbit dimensional precision and stability in the presence of dynamic disturbances from on-board instrumentation and nonuniform heating.

For example, the LDR proposed for the 1990s will be about 20 m across and require a surface accuracy of a few microns. The proposed CSTI program emphasizes high precision, lightweight panels for segmented erectable/deployable reflector concepts, in-space construction concepts, and methods to maintain micron-level control of the reflecting surface. This should lead to future R&D designed to extend precision structures technology to larger reflectors (on the order of 100 m across), arrays of reflectors, and wavelengths in the visible range.

A key element of both large space structures and precision structures is the need to predict accurately the on-orbit performance from analysis and ground test. In both of these areas the state of the art is inadequate to meet anticipated needs. As space structures become larger and more flexible, traditional test methods fail due to the overwhelming influence of gravity on the dynamics of the structure. Also, facilities do not exist for testing very large space structures or scale models which themselves will be large, nor

do good scaling methods exist. The analytical approach must be multidisciplinary, as with the CSI. A focused effort should be made to determine the limits of analytical prediction and ground-based testing and modeling. Methods then need to be developed to combine this capability with limited in-space experiments to provide the technology for accurate on-orbit behavior.

In the field of spacecraft dynamics and control, the main problem is the inability to devise "a priori" mathematical models of the precision required to meet spacecraft performance specifications. Increased computer power, energy, and instrumentation are needed to enable construction of correct mathematical models. Control systems must be constructed in such a way that they can learn about modeling deficiencies after the spacecraft is in orbit, make necessary adjustments of the mathematical model borne in the spacecraft computer, and alter the control system accordingly. Although there is substantial literature in the theory of adaptive control, none of it at its present stage of development can be directly applied to the class of problem at hand.

For future astronomy and planetary scientific studies, the LDR is a necessity. It must be carried into space as segments, assembled at the Space Station, and boosted to its proposed orbit as a free flyer. As noted above, the structure of the primary reflector is a major materials and structures challenge. Precision reflector panels and the methods of controlling their stability are major hurdles to be overcome.

The R&T areas should include:

- development of lightweight, high-stiffness, low coefficient of expansion, metal-matrix composites based on fiber-reinforced aluminum or magnesium matrices with very low CTEs;
- development of mathematical models that can be used in the spacecraft computer to make the necessary adjustments for on-orbit performance; and
- the ability to control pointing accuracy by the use of active controls based on electromechanical or other device concepts.

RECOMMENDATIONS

1. Understanding the processes in parallel with achieving improvements is essential in new structural and nonstructural materi-

als. The latest advanced metallic materials (especially magnesium-, aluminum-, and titanium-based materials) for advanced spacecraft applications should be fully characterized. Stress corrosion resistance, fracture mechanics characteristics, high- and low-temperature effects, and NDT limitations must all be studied in detail prior to supporting further alloy optimization.

2. In the nonmetallic material area, emerging structural composite materials systems at environmental extremes, especially cryogenic performance, need to be fully characterized. New work is needed to develop and characterize thermoplastic composite systems for space-unique applications. Resin-based composite systems must be characterized for potential outgassing in space to allow their utilization with cryogenically-cooled sensor systems and sensitive optics.

3. Thermal protection materials development should emphasize carbon-carbon materials technology through the following specific areas of investigation:

- evaluation of thermal mechanical properties and stability of carbon-carbon materials;
- development of processes and control of process parameters to yield consistent mechanical and thermal stability;
- evaluation of aerothermal structural interaction and coating and impregnation techniques to afford oxidation resistance and long-life reusability;
- low-cost fabrication concept developments;
- development of joining and structural assembly concepts to account for thermal strain anomalies; and
- analytical support to all development tasks covering effects of material and process variables of hardware performance, thermostructural performance, life-cycle effects, and design allowables.

In all cases of the high-temperature structural concepts to be investigated, there is an urgent requirement for major high-temperature materials and structural components test facilities. The development of such facilities is mandatory to ensure that an adequate data base of properties and design concepts can be evaluated to support future vehicle design.

4. Nonstructural materials for space also require a detailed understanding of the effects of the space environment. Interactions between materials and atomic oxygen must be understood; new protective coatings must be resistant to the space environment; methodologies are needed to evaluate accelerated space-environment life testing of materials in combined environments; and damage potential by man-made and micro-meteoroid orbital debris must be defined and its effect on space structures determined so that protective concepts can be developed. The spacecraft contamination potential for outgassing, life support, and propulsion system products must be evaluated. Solar and nuclear radiation effects on radiator coatings, solar panels, and the total spacecraft and payloads, especially effects on microelectronic devices, are required to ensure adequate design.

5. Ground-based simulation of the space environment must be fully developed to allow screening and evaluation of material improvements and supportability approaches. Degradation mechanisms must be studied to understand when simulative testing is reproducing the natural environment effect, in order to guide accelerated test methodologies.

Flight experiments may be necessary as an adjunct to materials and structures component testing, because of the inability to simulate the combined environments of temperature and flow to evaluate adequately the concepts. Data and structural concepts regarding these materials from DOD and SDI programs as well as the National Aerospace Plane program should be coordinated and made available so that a data base for design can be constituted in a reasonable time and at an affordable cost.

6. Recommendations for structural development and analysis include developing design and analysis tools and coming to a more complete understanding of relationships between the design process and system costs. To date efforts to predict damping have been unsuccessful, and more attention should be paid to designing predictable and controllable amounts of damping into the structure. Terrestrial facilities to test large space structures do not exist, thus control of large, flexible space structures will require mathematical models more precise than those available; therefore, R&T emphasis should be placed on systems that can "learn" after the spacecraft is in orbit and can alter controls automatically.

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Information and Control Systems

BACKGROUND

Information systems have been a growing portion of total mission costs. It is anticipated that in the Space Station era the information systems portion of operations costs could approach 50 percent for some missions. Industry and DOD make investments in information systems technology that dwarf NASA's total R&T funding levels. Much of NASA's information systems development reasonably depends on industry and DOD-funded development. There are NASA-unique needs that will not be met without NASA's R&T, however, and NASA must use its limited R&T resources wisely and selectively. NASA must determine unique requirements and "invent" only where the requirements are unique and find ways to take full advantage of university and industry development activities.

It should be noted that information systems R&T responsibility is shared within NASA. Some of the needed developments identified in this section will be appropriate for organizations other than OAST (such as the Office of Space Tracking and Data Systems and OSSA). Since information systems are so pervasive, this is a technology area that could benefit from increased focus, direction,

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and coordination among NASA offices and between NASA and DOD.

KEY TECHNOLOGY AREAS AND OPPORTUNITIES

Assuming manned deep-space flights of long duration (for example, a Mars mission), there are a number of conditions unique to such space flights that result in a need for substantial research and advanced technological development. Some of these unique conditions and requirements are the following:

- substantial signal delay due to signal travel time over interplanetary or high-orbit distances;
- frequency shifts in communication links during periods of vehicle acceleration due to vehicle thrusting;
- need for real-time and/or continuous voice and video communications;
- need for continuous (24-hour) tracking, command, and control capability; and
- vulnerability of electronic circuits to cosmic radiation.

The Space Station program and associated co-orbiting and Polar platforms, plus the anticipated increased importance of understanding man's effect on the Earth as a system, will provide the following additional unique conditions and requirements:

- an explosion in the volume of information gathered in space and a need for automated preprocessing and rapid and wide dissemination of information products;
- sensor data-rate capabilities that outstrip telecommunications capabilities; and
- a continued shift of emphasis in the driving scientific questions that cut across traditional discipline boundaries.

With these unique considerations in mind, the committee proposes a number of functional areas that need advanced development:

1. High-speed, low error-rate digital transmission over long ranges: The task must be to achieve the maximum bits-per-hertz transmission within bandwidth, power, and mass constraints with very high real-time information rate requirements. The complexity of future missions will force the need for very high-rate uplink (command) information systems where reduced error-rate requirements

are increasingly stringent and the power and mass constraints shift to the receiving side of the system. Research is needed on data compression techniques (both information preserving and degrading depending upon application) at very high rates. Forward error-correction techniques must be developed applicable to very high rate data for both random and burst errors since the probability of interruptions due to environmental interference (e.g., from solar flares) is high. Compensation must be made for interruption of high-speed vital links for long periods of time. Extensive computer-to-computer interactive transmission will be required with techniques that can accommodate long-life, travel-time delay effects. Systems must be able to accommodate large frequency shifts and large rates of change of frequency during periods of vehicular acceleration.

2. Voice and/or video communications when continuous real-time communication is required: Examples include crew-to-crew, crew-to-land base, crew-to-orbit, crew-to-Earth, and crew-to-remotely operating vehicles. The real user requirements for video update rate and resolution, and the resulting bandwidth, must be determined.

3. Space-borne tracking and data relay capability: Present plans for data relay satellite systems must be studied and augmented for future requirements, such as manned interplanetary missions. In addition, space-to-space link requirements need further study.

4. Command and control: Earth-based computers will need enhanced capability and speed for real-time command and control, including simulations of actual flight conditions. Real-time reconstruction of images with adequate resolution is a problem while transmission signals experience long travel-time delays. Effects of delay on the whole command and control function must be assessed and compensation made. Further comments of this topic are included in the next section.

5. Sensors and instruments: Special instrumentation is needed for the detection of hazards to astronauts and life support equipment within spacecraft or on planet surfaces. It is also needed to carry out the spacecraft's operational functions, such as monitoring of conditions and housekeeping.

6. Deep-space tracking and data acquisition: Further manned and unmanned deep-space requirements must be met by the proper combination of ground-based, Earth-orbit, or Moon-based systems.

Technology must be pursued for moving to higher radio frequencies and optical communications.

7. Ground-based data management: This is an area that has been well studied by several committees, including the National Research Council's Space Science Board which issued a report, *Issues and Recommendations Associated with Distributed Computation and Data Management Systems for the Space Sciences.* It is generally believed NASA should make a greater effort in this area since the problem will grow drastically over the next 20 years. Much of the area falls outside of OAST's role in NASA, but some specific technologies could use OAST's attention.

Data volumes will increase by orders of magnitude with attendant challenges on short-term (buffering) and long-term storage; data location, access, and distribution systems; and decentralization.

8. Ground-based data analysis: Needs for ground-based data analysis include cost-effective high-capability work stations, data visualization, and automation of analysis tools and techniques. Some categories of problems will drive continued Class VI computing development, and some categories of problems will drive interactive instrument monitoring and control.

9. On-board computer computation: Space-borne computers have a lag, compared to ground-based state-of-the-art computers, typically in excess of 15 to 20 years. The mission needs for on-board processing anticipated over the next 10 to 20 years equal and in some cases exceed today's capability. The difficulty of duplicating ground-based compatibility goes far beyond a simple problem of repackaging. Space presents power and weight constraints, but also unique environmental problems, the foremost of which is radiation and heavy charged particle bombardment outside of the protection of the Earth's magnetic shield. There are also unique functional requirements of extended useful life, reliability, fault protection, and autonomous fault recovery.

Processor applications that include command monitor and control of critical systems and subsystems push the reliability requirements beyond any ground applications needs. There are also unique needs in specialized applications, such as signal processing for particular sensors.

NASA needs a research program to address these computing

issues and focus on design or qualification of autonomous space computing systems. DARPA programs are focused on very advanced computing architectures (not necessarily designed for space) applied to specific terrestrial applications. SDIO is focused on providing a generic technology base, such as very high speed integrated circuits (VHSIC), for massive in-space processing applications requiring thousands of computers for battle management.

The computer technological areas that follow discuss general requirements, common across almost all flight data systems, and areas more unique to control, specialized processing, robotics, and storage and optical technology.

General requirements include:

- High reliability for extended periods, minimum power and mass, and significant increase in capacity and speed.
- Monitorability of state and status: One generally cannot afford to "cold-start" space-based processes except under limited and controlled situations. Fault protection and recovery methods are, therefore, required to track recovery events and/or to "roll back" to a previously known total system state.
- Protection from radiation and heavy charged particle bombardment: This is a vitally important technology area. It requires technical solutions at all levels, from the physics of devices and device (software) architecture. Techniques currently being applied to CMOS technology are known not to be applicable to the VHSIC scale of components. The current DOD VHSIC program is not addressing the issue.
- Variety of input/output types and rates: Processor needs vary significantly between missions and between applications within a particular mission. This means a simple generic data system will not be able to meet all needs.
- Challenging trade-offs between software and custom firm ware implementation: Some applications needs will be most practically met with a combination of software in a general-purpose processor, software in a specialized processor, and hard-coded instructions in hardware ("firm ware"). Making the right choices will require basic research in some areas, and development and demonstration in others.

Control Applications

In contrast to the general areas, control demands ultra-high reliability but relatively moderate speed. In addition, autonomous fault recovery is mandatory to ensure uninterrupted operations for critical functions.

Space automation computing requirements present further special technology challenges. Space autonomous systems (as discussed in Chapter 8) in the long term will need to be merely supervised, rather than directed or continuously monitored, by humans. This means their computers must be validated to an unprecedented degree.

Autonomous systems will require a network of distributed computers for efficient operations. Therefore, the above requirements apply not only to computers but to on-board data storage and data transfer technologies. Specific research in computing architecture, electronic parts, and operating systems for autonomous command and control in space is needed.

Data and Signal Processing Applications

Data processing requires ultra-high speed but moderate reliability in relation to control applications. Signal processing for modest-rate instruments may be possible in foreseeable general-purpose processors. When the rate and complexity increases (the technology is in hand with which to build sensors in excess of 1,200 Mb/sec raw data rates) then the only feasible solutions involve custom processing using computer architecture specialized to the particular applications (typified by, for example, systolic arrays and wave-front processors). It will also be appropriate for portions of the process to be in special-purpose hardware, such as VHSIC or optical electronic components. Information extraction to achieve bandwidth reduction must be as close to the source as possible.

This is a special case of signal processing but represents in general a class of calculation complexity that pushes processing speed requirements even further. It is also a very fertile basic research area for algorithm development.

Robotics

Robotic systems will require a variety of computer capabilities:

AI computing for machine decision making, high-speed numeric processing for manipulator control, and image recognition, highly fault tolerant computing for real-time system control. These systems must perform this wide variety of computing within constraints imposed by the space environment.

Remotely operated robotics, such as might be used for servicing geosynchronous satellites or roving on Mars, will place the most stringent low mass and power requirements on autonomous computing.

The ultimate goals of robotics will require applying a full spectrum of information systems technology and classes of processors, both general and special purpose. For example, the feasible solutions to the robotic vision problem will most likely require a combination of a special purpose processor near the sensors staging higher levels of information extraction through a hierarchy of processors until the needed information is passed to the controlling "brain."

Storage and Optical Technology

One can envision processors that utilize some combinations of optical and digital processing. Most likely the applications will be very specialized but with significant potential for making certain processors practical within space weight and power constraints. Storage must be pushed to terrabyte levels for downlink channel rate buffering and channel outage protection of critical data. Increased lifetime requirements in the space environment are needed, and low-error rate is essential.

Optical storage technology is often viewed as the coming savior for NASA's massive data staging and storage needs. Unfortunately, commercial technology needs do not require space qualifications nor even approach the very high (greater than 100 MB/sec) input/output rate required by NASA applications. Optical technology has promise but adaptation to NASA's space needs may require fundamental development. Other nontape solutions should be basic research topics; however, further development of tape technology will be required for at least 10 to 15 more years.

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Sensors

BACKGROUND

The primary objective of NASA's Space Science program, as mandated by the Space Act of 1958, is to expand human knowledge. The primary objective of NASA's Space Applications program is to apply the knowledge and technology developed by all NASA programs to the solution of practical problems and the creation of commercial products. Principal applications are communication and navigation satellites and government-supplied public services, such as weather and climate forecasts. DOD and NASA conduct research in space on the nature of the near-Earth environment and in response to military requirements.

The data to expand human knowledge and provide practical applications arrives at a spacecraft in the form of photons or particles. Sensors collect these photons or particles, measure their intensity, wavelength, or mass, and determine the direction and time of their arrival. Arrays of detectors provide images.

Direct human observations, sample return from the Moon or planets, and laboratory research aboard the Shuttle or Space Station are the only cases where information is acquired other than by the detection of photons or particles.

Leadership in sensor technology is essential to leadership in

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space science and applications. From the first U.S. satellite, Explorer I, to the current most sophisticated observatory, the HST, operational sensors have benefited from technology development. Research sponsored by the Office of Naval Research provided the Geiger counters used to detect the radiation belts; the star trackers of the HST evolved from a decade of star-tracker technology.

Sensors and instruments began as small, simple devices that weighed a few pounds, cost $100,000 to $200,000, and could be produced in a university or government laboratory instrument shop. Today's instruments may weigh 1,000 kg, cost more than $100 million, and require a team of contractors to produce. The time from conception of a new instrument to the production of useful data has correspondingly increased from one to two years in the early 1960s to 10 to 20 years in the late 1980s. Payloads vary from a single complex instrument such as the IRAS infrared telescope and its detectors to a collection of 20 to 30 instruments on a Spacelab mission. The quantity of data which must be collected, processed, transmitted, and stored has increased from 10 bits per second to 300 megabits per second and can be expected to increase at least another order of magnitude in the period covered by this report.

Sensor technology may be generic technology to develop a new class of infrared detectors or specific, mission-directed technology to produce the infrared instruments for the IRAS satellite. OAST generally develops the generic sensor technology and the Office of Space Science and Applications develops the instruments for a particular mission.

STATUS

Photon detectors exist for the entire electromagnetic spectrum from long wavelength radio waves to billion-electron-volt gamma rays. Particle detectors exist for particles whose mass ranges from electrons of 10^{-27} grams to milligram dust particles, and whose energy ranges from 1 to 10^{15} electron volts. Arrays of photon detectors exist that can provide images of the Earth's surface with a resolution of less than 10 meters.

Sensor technology should continuously strive to improve the sensitivity of sensors and their spatial, spectral, angular, and time resolution. The number of detectors per unit area needs to be increased to improve image quality. Reduction of noise through

cryogenic cooling of detectors is required to improve the sensitivity of the detectors.

OPPORTUNITY

The sensors and payloads of future space science and applications will continue the long history of pressing for greater and greater spectral, radiometric, angular, time, and spatial resolution. The relative emphasis among these parameters varies from discipline to discipline and shifts with time within a discipline.

At any given point in time, however, there will be many attractive objectives for R&D. NASA must have an ongoing and systematic process for the identification and ranking of those objectives. The NASA long-range plan and the available mission lead times are key inputs to that process.

Close cooperation between OSSA and OAST, and, where practical, jointly-funded projects, advance generic technology at the most rapid rate into most useful areas and produce the most advanced and useful instruments.

KEY AREAS FOR TECHNOLOGY DEVELOPMENT AND RECOMMENDATIONS

Four principal areas are recommended for sensor systems R&D along with two supporting areas. The principal areas are:

- Large aperture optical and quasi-optical systems
- Detection devices and systems
- Cryogenic systems
- In-situ analysis and sample return systems

The supporting areas are:

- Radiation insensitive on-board computational systems (hardware and software)
- High-precision attitude sensors and axis transfer systems

Further, there are essential couplings to companion R&D tasks in such areas as materials, structures, automation, and robotics. Each of the principal and supporting areas are discussed herein.

Large Aperture Optical and Quasi-Optical Systems

From the near-ultraviolet through the submillimeter wavelengths, optical and quasi-optical energy collection and detection systems are employed. Reflective optical trains direct received energy to photodetectors, bolometers, and mixers suitable to the operating wavelength. The continued advancement of the sciences and applications employing these wavelengths require enhancements in collected energy and/or spatial resolution, as well as a corresponding increase in the diameter of the collecting aperture.

This task is directed at the technologies enabling the use of such larger apertures. Those technologies include the fabrication and deployment of solid and segmented apertures and associated subreflectors, coatings, and means to assure mechanical integrity and alignment under all expected mechanical and thermal conditions.

One objective of this work is to reduce the weight of collecting apertures through novel structural techniques and adaptive control techniques. Another is to improve the rejection of stray radiation, the reflectance of key surfaces, and the reduction of surface contamination. Encompassing all of these activities is the overall control of thermal and structural properties. In active sensing systems, the use of high-power lasers will add special problems.

The aperture diameters employed are obviously a function of wavelength, but range from several feet at short wavelengths to as much as 10 or more feet at long wavelengths. The usability of a large aperture is affected by not only its own construction but by exterior conditions (e.g., coupled vibration) and related subsystems (e.g., remote optical axis transfer).

In some instances, notably the x-ray and far ultraviolet regions, conventional optics (using near-normal incidence angles) must be replaced by grazing incidence designs. Such designs pose special problems in coatings, fabrication, alignment, and the maintenance of long-term, high throughput.

It is expected that this, and other tasks described in this section, are performed on a continuing level-of-effort basis. Tasks will be ranked and undertaken as that level permits. Close coordination is essential with defense-related segmented optics programs, as well as ground-based astronomical studies.

High-Sensitivity Detection Systems

Accompanying the improvements in optical systems discussed above are the improvements and trade-offs in the detection systems that will be placed in their focal planes. Over the long term, NASA's science and applications programs are likely to employ every part of the electromagnetic spectrum. In the near term, scientists forecast that major discoveries are expected in the x-ray, far ultraviolet, infrared, and submillimeter regions. It is these areas that will receive the initial attention. As in the preceding task, the effort is characterized by a continuing level of effort, with priority assigned on a slowly shifting basis as science and application interests evolve.

X-ray detectors are limited in efficiency, self-noise, and the minimum attainable fixed size. Far ultraviolet detectors have limited spectrometric resolution that may be amenable to improvement using holographically produced diffraction gratings. In the infrared, continuing work is required on the sensitivity, durability, and uniformity of detector arrays, and materials are needed for higher temperature operation. For submillimeter wave systems, essentially every aspect requires improvement, a reflection of the comparative immaturity of this technology. All of these elements of improvement will be addressed.

Cryogenic Systems

Detectors operating in the middle-to-far infrared and beyond require cooling to cryogenic temperatures from less than 2°K to typically 100°K. In some instances, the entire telescope or optical train must also be cooled. A variety of means have been used in the past to achieve these temperatures, with the most successful using solid cryogens or passive radiative cooling.

The increasing demands of detector systems, in terms of diminishing operating temperatures and the arraying of multiple detectors in the focal plane, pose difficult R&D challenges. In both instances, the amount of heat conducted from ambient temperature electronics to cold-plane detectors must be markedly decreased over current techniques. Contamination of the cold plate and surrounding reflective surfaces in passive coolers must be similarly decreased, another difficult challenge.

In some instances, the achievement of sufficiently long life from a costly instrument may not be feasible in the absence of on-orbit

servicing and refurbishment. In this case, special development efforts are required to enable a designer to include plans for on-orbit replacement of cryogenic elements of a sensor system.

In-Situ Analysis and Sample Return Systems

The preceding tasks all fit under the general technique of remote sensing. These same technologies, with others, can support in-situ analysis of lunar and planetary samples or the selection of samples for return to the Earth. Passive and active spectrometric techniques are a fertile area to extend the capabilities of future unmanned planetary missions or scout missions that precede the landing of humans on Mars.

Supporting Areas of Technology

While on-board computation is addressed elsewhere in this report, it is worth noting that it is a mandatory capability for the deployment, management, and control of advanced space-borne sensing systems.

Similarly, sensor systems must be coupled to the spacecraft bus and its attitude determination and control capability. If the bus is large, the sensor designer must be prepared to either transfer a known pointing reference from a distance point or provide an autonomous capability to derive pointing references. There is also the related issue of attitude knowledge and data tagging versus pointing control and/or autotrack. All of these interact strongly with the design of a sensing system.

The "Task Quantum"

All of the above tasks have been characterized in terms of a broad level-of-effort, rather than singular research tasks having a single or limited number of preplanned outputs. Each of these research areas must be a permanent part of NASA's activities. The specific subtasks and their emphases will change with time, but the need for work in these general areas will not. The pursuit of a balanced space program requires a balanced technological underpinning.

With the above in mind, it is appropriate to define a "task quantum" as the minimum sustained effort that produces the long-term

benefits of consistent progress and operation at or above "critical mass." First, it is necessary to state two ground rules: (1) a technology task includes component development, but also may include further work to establish proof of concept, and (2) the task should be performed as a joint effort by NASA and industrial or academic partners. In the latter instance, the NASA participants must serve as technical contributors, as opposed to simply contract or grant monitors who add to overhead rather than progress.

Under these ground rules, a "task quantum" for a significant advance of sensor technology will consist of a NASA team and an industry or academic team. The latter will frequently consist of six professional (a typical skill mix might be one or two physicists, a chemist, and four engineers—two junior and two senior) and four technicians. This level of effort represents a nominal annual contract value of $1.5 million to $2.0 million, depending on the subcontracted materials and parts required.

The NASA side of the team (funded through the Research and Program Management—R&PM—budget) would consist typically of a project leader, administrative support, four professionals (two physicists and two engineers may be representative), and two technicians. The government side provides not only its share of activities but also serves as the long-term corporate memory.

Initial Tasks

A representative set of tasks that could be chosen is:

- Large aperture segmented optical system for near ultraviolet to far infrared wavelengths
- Advanced grazing incidence x-ray system
- Large aperture deployable microwave radiometer antenna
- High-quantum efficiency, quantum-limited, ultraviolet detector system technology
- High-quantum efficiency, quantum-limited, x-ray detector system technology
- High-sensitivity submillimeter wave receiver technology
- Advanced radiative cryogenic cooler technology
- Advanced solid cryogenic cooler technology
- In-situ analysis technology
- Sample selection and return technology

This represents an augmentation of NASA effort in the sensor area of $15 million to $20 million per year, and an accompanying allocation of approximately 80 NASA personnel for sensor technology.

Part III:
Conclusions and Observations

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Conclusions and Observations

Eminence in space offers economic advantages as well as national security and prestige benefits. In 1986, for example, the United States' aerospace balance of trade surplus was $10.9 billion—the eighth consecutive year it had been over $10 billion. In the last decade, the space component of the U.S. aerospace market quadrupled with a 16 percent revenue growth compared to 11.5 percent for the entire aerospace industry (see Appendix A).

The exploration and use of space is a young field, at an early stage of development, with great potential to absorb usefully technological investment. European, Japanese, and Soviet governments, recognizing this potential and the benefits to be gained, have aggressively targeted space and aeronautics as strategic industries for the twenty-first century. The question is no longer one of U.S. preeminence, but of retaining a competitive status. Historically, the United States has looked to NASA to provide the technology base upon which U.S. industry and the civil and defense sectors could draw. Yet, since the Apollo program, U.S. commitment to space has been checkered. As discussed in the preceding text, many programs have been started only to be terminated before the technologies were ready to be applied. For the last 15 years, less than 3 percent of the NASA space budget has gone toward research and technology

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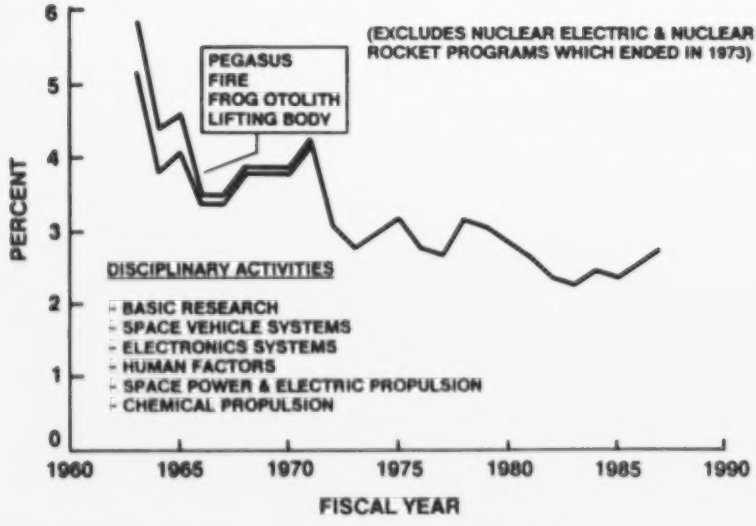

FIGURE 14 NASA space R&T budget as portion of total NASA budget.

development (Figure 14). This is an inadequate investment to ensure a competitive position for the United States in coming decades and to provide the nation with the advanced technology for future civil and defense options.

The deterioration of funding for space research over the last 20 years is striking (Figure 15). If NASA is to fulfill the mandate of the Space Act and meet serious national needs, an adequate level of support must be assured for R&T.

In its deliberations, the committee judged eight space technology areas to be of high priority; examined requirements for potential technological advances in those areas; and estimated broadly the range of investment required to enable NASA to conduct an adequate program. Highest priority was placed on developing advanced propulsion systems and the second highest on those technologies applying to human space travel, including life support systems, automation, and robotics. The traditional disciplines of power, materials, and structures ranked third, followed closely by information systems and sensors. In approaching appropriate funding levels, the minimum level required to maintain a critical mass and produce useful results was considered, then a desirable, truly enabling level was

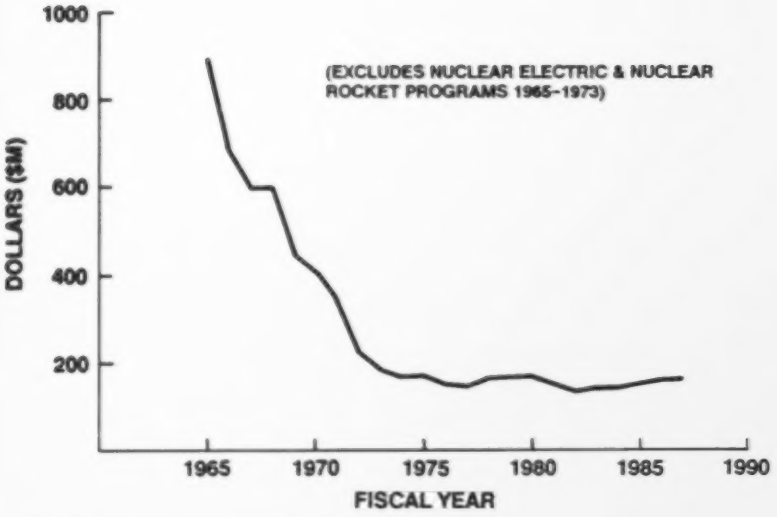

FIGURE 15 NASA space R&T funding trend.

determined. The committee's recommendations regarding general levels of budget augmentation to permit recommended technological advances are presented in Table 4. These recommendations are derived from the program activities proposed in preceding chapters on the basis of the committee members' experience and NASA cost estimates.

The committee determined the suggested augmentation levels by taking into consideration not only research costs, but necessary facilities and support for demonstration projects where those were deemed to be essential. Examples of these are special purpose facilities for testing advanced chemical propulsion test-bed engines, vacuum chambers for testing large electric propulsion systems at megawatt power levels, environmental control and life support test-bed systems, and special hardware for in-space experiments. However, in a more generic sense, a research and technology program three times the current level may require significant expansion or modernization of existing laboratory facilities. An example would be ground facilities to support an expanding in-space experiments program, i.e., experimental hardware integration and test facilities.

TABLE 4 Recommended Funding

Technology	Minimum Augmentation ($Million)	Desirable ($Million)
Propulsion	200	300
Humans in space	35	125
Automation, autonomy, and robotics	75	125
Life support	25	100
Power	75	75
Materials and structures	50	75
Information systems	50	75
Sensors	15	20

This type of institutional capability was not considered in depth by the committee in its recommended augmentation.

As is customary in NASA budgets, personnel costs were not included in the recommendations. It was recognized that, were the funding available, it would take several years to bring in new scientists, engineers, and other personnel and to put accelerated programs into place. Assuming such a ramp up can take place, a detailed funding profile was not believed to be an appropriate exercise for this group. The point the committee wished to make was that a minimum level of assured support is essential if advances are to be made. The justification for this le l of investment lies in the importance of space technology for nat nal security, prestige, and trade competitiveness.

Figure 16 illustrates comparative funding levels for both the lower limit and the desirable program. Figure 17 compares funding for the entire Fiscal Year 1987 space technology program and that being sought by the Office of Aeronautics and Space Technology (OAST) for FY 1988 with the desirable level—i.e., that viewed by the study committee as necessary and enabling. It should be noted that life support research is conducted in the Office of Space Science and Applications and the above recommendation is intended to augment existing support; the other figures represent total recommended R&T investment. Outside of the above technologies that

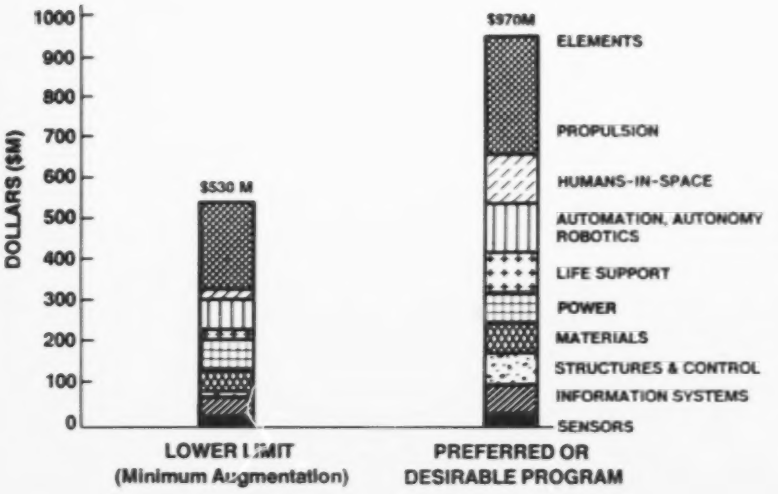

FIGURE 16 Recommended funding.

the committee selected as highest priorities, in the 1988 budget approximately $51 million addresses other areas that OAST pursues to maintain a balanced program. Incremental approaches in current research and development programs and planning appeared to the committee to meet anticipated needs. (Such programs include navigation and guidance, aerothermodynamics, aerobraking, system studies, and cooperative experiments.) Depending upon the specific requirements of any given year, demonstration programs may increase requirements above the $905 million level. Technology development for the National Aerospace Plane is not included in these calculations.

RECOMMENDATION

Based upon its examination of technology development requirements, the committee recommends that for the next decade the NASA R&T effort in this area not be allowed to go below 7 percent of the total NASA budget and that these resources be protected from short-term requirements of major operational programs.

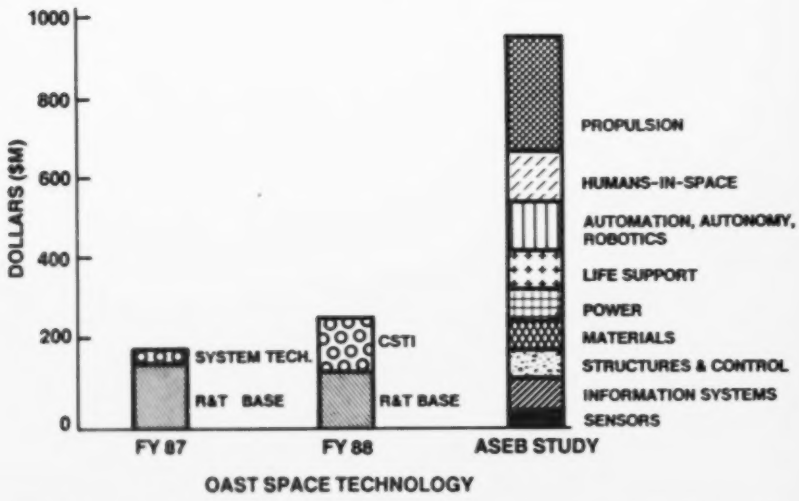

FIGURE 17 Preferred program contrasted with existing program and anticipated FY 88 augmented program.

SUMMARY OF REPRESENTATIVE MISSIONS

This study attempted to identify key technologies where contemporary investments might have large payoffs in technological options for the future. The committee considered future needs for space transportation, space science, national security, and manned missions then selected sets of representative missions and the essential technologies to enable those missions. It identified eight areas as being vital to the nation's future in space. Findings regarding representative mission sets and the recommendations concerning high priority technologies are summarized below.

In the first four chapters, "driver missions" were considered, i.e., the types of missions the nation might hope to undertake within the next 30 years for which challenging advances in technology will be required. Future transportation needs were identified and include modern launch systems of small and medium capacity, unmanned heavy-lift capability, a reusable orbital transfer system, a Shuttle replacement, and a high-energy interplanetary transfer system.

Potential space science driver missions for the mid-1990s were represented by the Earth Observing System, the Large Deployable

Reflector, and the Mars Sample Return Mission. The long-range (2015) space science missions selected on the basis of their technology drivers were: a Coherent System of Modular Imaging Collectors (COSMIC); a COSMIC Interferometer; a solar probe, a Venus sample return mission; the Thousand Astronomical Unit mission; colonies on the Moon, and human exploration of Mars. It was clear that space science missions, many of which are performed with existing technologies, can actually provide any degree of technological challenge and that science and technology must proceed hand in hand.

Defense space R&T requirements included communications, navigation, meteorology, attack warning and assessment, reconnaissance and surveillance, and transportation to space. NASA's role was seen as being threefold: (1) to advance the state of common technologies thereby creating new opportunities for the defense establishment, (2) to work closely with the U.S. Department of Defense in anticipating long-term defense technology needs, and (3) to optimize the interaction between the two organizations by active cooperation at both leadership and technical levels.

The last category of missions considered was manned exploration. The technology driver was obvious and one that may prove to be an important option for the nation, a manned mission to Mars.

MEETING THE TECHNOLOGY CHALLENGE

In the subsequent eight chapters, challenging technological advances that could enable these missions (and more) were examined. The areas selected were viewed as those requiring the greatest emphasis in coming years if NASA is to rebuild the national R&T base. As noted, NASA conducts research in other areas at what the committee judged to be effective levels, and no major changes are suggested in those programs.

Propulsion

Advanced propulsion should be afforded the highest priority and a new generation of technology should be pursued to support U.S. launch requirements. Specifically, NASA should pursue engine design and development activities for:

- a range of advanced Earth-to-orbit engines;
- reusable, cryogenic, orbital transfer vehicle engines (fault tolerant, reliable, long-lived);
- high-thrust (greater than 10,000 lbs) and/or high-performance (Isp greater than 860) orbital transfer propulsion systems for manned Mars and similar missions; and
- high-performance (Isp greater than 1,200), low-thrust primary propulsion systems for solar system exploration spacecraft.

Support for development of generic technologies, such as turbines, seals, and valves should be held separate from major development activities, i.e., as the need for major system demonstrations becomes apparent, funding for hardware demonstration should be identified separately.

Technology to Support Humans in Space

Before proceeding with long-duration manned missions beyond Earth orbit, NASA should address the following issues:

- microgravity effects on the cardiovascular and musculoskeletal systems;
- protection against solar and cosmic radiation;
- closure of the life support system;
- the need for artificial gravity;
- improved equipment for extravehicular activity;
- augmentation of human capabilities with autonomous and/or robotic systems; and
- human factors, including crew selection and training, man-computer interface, and communications.

Systematic human and long-duration animal experiments will be required to assess deconditioning and evaluate protective devices and protocols. If effective countermeasures cannot be determined, artificial gravity will be required. The Space Station should be used for long-duration experiments and to begin artificial gravity experiments.

Life Support Systems

Actually a subcategory of the above, life support includes providing and recycling water, food, and air as well as thermal control.

NASA should proceed with research on closed life support systems and with equipment technologies to improve personal hygiene procedures. Use of extraterrestrial resources must be explored to support lunar or Mars bases. Systems development modeling and analysis tools need emphasis to ensure that the various technologies can be properly molded together.

Automation, Robotics, and Autonomous Systems

Automated systems can augment human capabilities by performing mundane, repetitious, or dangerous tasks, and can both increase human productivity and conduct tasks infeasible for humans; automation will be increasingly important in unmanned missions as well. While much can be gleaned from terrestrial experience, microgravity, long transmission delays, and the space environment dictate special design and protection considerations. Light, limber manipulators will interact with dynamically active elements such as structures, transportation elements, and free-flying satellites. Advanced sensing and control techniques will be needed to sense the environment and interact with the tasks. Artificial intelligence will be needed for advanced information processing, along with trainable systems for unknown environments.

Power

As energy requirements for scientific, military, and commercial missions increase, there will be a need for larger, more utility-like energy systems. Desirable power supplies include photovoltaic, solar dynamic, and nuclear; however, only nuclear reactor generated power can meet very high requirements. The space nuclear power program has a start-stop history. It is recommended that NASA increase its participation in the SP-100 program to ensure that its own future requirements for high energy are met. R&D on photovoltaic, solar dynamic, Stirling engine, and other power conversion development should continue.

Materials and Structures

Advanced metallic materials, via alloy synthesis, offer the greatest potential for dramatically increasing payload to orbit. Development of improved performance resins will dramatically increase

the utility and applicability of composites on advanced space structures. Warm/hot structural advances offer a more cost-effective means of countering reentry heating than is presently afforded by thermal protective systems.

Understanding the processes in advanced metal research is essential, and these materials should be fully characterized before application to spacecraft. Prior to further alloy optimization, issues such as stress corrosion resistance, fracture mechanics characteristics, high- and low-temperature effects, and nondestructive testing limitations must be studied. In nonmetallic materials, emerging structural ceramics and composite materials systems need to be fully characterized, especially their cryogenic performance. Resin-based composite systems must be characterized for potential outgassing in space to allow use with cryogenically cooled sensor systems and sensitive optics. Thermal protection materials development should emphasize carbon-carbon materials technology. There is an urgent national need for test facilities for high-temperature materials and structural components.

It is recommended that NASA avail itself of developments in materials sciences in industry, universities, and DOD and concentrate on space-unique requirements.

Information and Control Systems

Again NASA must make the best use of technology available from industry, DOD, and universities, and direct its own research to space-unique systems. NASA's research program should focus on design of autonomous space computing systems and address the computing areas discussed in the text: high-speed, low-error-rate digital transmission over long distances; voice and/or video communications when continuous real-time communication is required; space-borne tracking and data relay capability; enhanced on-board computing capabilities; instrumentation to monitor equipment condition and avoid hazards; deep-space tracking and data acquisition; and ground data handling, storage, distribution, and analysis.

Sensors

Sensors collect photons or particles, measure their intensity, wavelength, or mass, and determine the direction and time of their arrival. Arrays of detectors provide images. Leadership in sensor

technology is essential to leadership in space science and applications. Four principal areas and two supporting areas are recommended for NASA research and development. The principal areas are: large aperture optical and quasi-optical systems; detection devices and systems; cryogenic systems; and in-situ analysis and sample return systems. The supporting areas are radiation insensitive on-board computational systems and high-precision attitude sensors and axis transfer systems.

Last, while this committee's task was not to examine systematically the availability of scientific and technical personnel, the members believe this is an important national resource and that academic aerospace training should be strengthened. It strongly supports NASA efforts in this regard, such as creation of centers of excellence in space technologies at universities, but recommends a more aggressive emphasis in university engineering programs on the high-priority space technologies discussed in this report.

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Biographical Sketches of Committee Members

JAY E. BOUDREAU is a staff member in the Space Nuclear Power Program Office at Los Alamos National Laboratory; Los Alamos, New Mexico. Over the past 15 years he has held management positions as Alternate Group Leader, Group Leader, Program Manager, and Deputy Associate Director for Nuclear Programs. His background is in reactor safety; between 1979 and 1981 he worked on the U.S. Senate Three Mile Island Investigation and with the Office of Management and Budget. He is author or co-author of over 40 published papers and holds a B.S., M.S., and Ph.D. in Engineering from the University of California at Los Angeles.

ROBERT H. CANNON, JR., is Charles Lee Powell Professor and Chairman of the Department of Aeronautics and Astronautics at Stanford University. His current research, with about 20 Ph.D. candidates, is in Space Robotics. He is also Chairman of NASA's Flight Telerobotics Servicer Advisory Committee. Earlier, from 1974 to 1979, he was Professor of Engineering and Chairman of the Division of Engineering and Applied Science at the California Institute of Technology. Between 1970 and 1974 he was U.S. Assistant Secretary of Transportation. Prior to that he had been Chief Scientist of the U.S. Air Force, a professor at the Massachusetts Institute of Technology (MIT), and a researcher in flight control

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and inertial navigation systems in the aviation industry. He has served as Chairman of the National Research Council Assembly of Engineering and as a Council Member of the National Academy of Engineering. Dr. Cannon received his Sc.D. degree from MIT in 1950. He has published a book, *Dynamics of Physical Systems* (1967), as well as numerous articles and papers.

ROBERT S. COOPER is President, Chief Executive Officer, and Chairman of the Board of Directors of Atlantic Aerospace Electronics Corporation. Throughout more than 25 years of involvement in military and space technology, he has held positions that include: Director of the Defense Advanced Research Projects Agency (DARPA) and, simultaneously (1981-1985), Assistant Secretary of Defense for Research and Technology; Engineering Vice President of Satellite Business Systems; Director of NASA Goddard Space Flight Center; and Division Director at MIT's Lincoln Laboratory. Dr. Cooper's research and development background extends to electromagnetic wave propagation in plasmas and plasma physics; laser systems engineering and laser atmospheric transmission; infrared optical instrumentation, focal planes, atmospheric transmission, and astronomy; and telescope pointing and tracking systems. He holds an Sc.D. degree in Electrical Engineering and Mathematics from MIT.

WOLFGANG H. DEMISCH is Vice President for Research at the First Boston Corporation, where he is responsible for equity research regarding the aerospace industry. Born in West Germany, he has been on the All-American Team of Aerospace Analysts since 1976. After graduating from Harvard Business School in 1972, Mr. Demisch worked at Smith Barney Harris Upham & Co., Inc. for eight years, and then at Morgan Stanley, Inc. Before attending business school, he had worked for three years with IBM Canada as a programmer and systems analyst. He received his B.A. degree in chemistry from Princeton University. Mr. Demisch is a member of the American Institute of Aeronautics and Astronautics, the American Association for the Advancement of Science, and the Financial Analysts Federation. He also serves on the NASA Advisory Council.

EMANUEL J. FTHENAKIS is Chief Executive Officer and Chairman of the Board of Fairchild Industries. He had been Executive Vice President in charge of the company's Communications,

Electronics, and Space Group. Mr. Fthenakis joined Fairchild in 1971 as Director of Information Systems at the Space and Electronics Division, and was founder and Chief Executive of American Satellite Company during its formative years. A native of Greece, Mr. Fthenakis graduated from the National Polytechnic University of Greece and from Columbia University in New York. He was a member of the technical staff at Bell Laboratories and later joined General Electric Company's Space Division as Director of Engineering, where he was involved in the development of strategic reentry vehicles and other missile programs. Between 1962 and 1969, Mr. Fthenakis founded, organized, and directed the Ford Space Division and was responsible for developing the first U.S. military communications satellite system. In 1982 he received a presidential appointment to serve on the National Security Telecommunications Advisory Council.

JACK L. KERREBROCK is Associate Dean of Engineering and Richard Cockburn Maclaurin Professor of Aeronautics and Astronautics at the Massachusetts Institute of Technology. From 1978 to 1981 and from 1983 to August 1985, he headed the Department of Aeronautics and Astronautics at MIT. Dr. Kerrebrock was Associate Administrator for Aeronautics and Space Technology of NASA from July 1981 to July 1983. He has taught and conducted research in energy conversion and propulsion since 1956 when he received his Ph.D. degree from the California Institute of Technology. His early work was on nuclear rockets, space propulsion and power, and magnetohydrodynamic generators. More recently, he has addressed the fluid mechanics of turbomachinery for aircraft engines, and is the author of a text on aircraft engines and gas turbines. He was Director of the MIT Gas Turbine Laboratory from 1968 to 1978. Professor Kerrebrock is a past and present member of several governmental advisory groups, including the National Commission on Space and the Air Force Scientific Advisory Board. He was decorated by the U.S. Air Force for Exceptional Civilian Service in 1981 and received the Distinguished Service Medal from NASA in 1983.

RICHARD KLINE is Vice President and Deputy Director of the Space Station Program Support Contract at Grumman Corporation. He had been Program Vice President of Grumman's Space Systems Division between 1983 and 1986. After receiving his M.S. in mechanical engineering from Princeton University in 1956,

Mr. Kline held various technical management positions in space-related areas at Grumman. Responsibilities have included management of the Apollo Lunar module manned systems test program in the mid-1960s, management of the Grumman Shuttle technical support contract, and direction of Grumman's Space Station systems analysis study. He has been elected to membership of the International Academy of Astronautics, is a director and Fellow of the American Institute of Aeronautics and Astronautics, and is a Fellow of the American Astronautical Society.

JAMES J. KRAMER is Manager of Advanced Technology Programs in Washington, D.C., for the General Electric Company. He assumed that position in 1982 after having been Manager of Strategic Planning for the General Electric Aircraft Engine Group. Mr. Kramer came to General Electric after 29 years with NASA and its predecessor, the National Advisory Committee on Aeronautics (NACA). He joined the technical staff of the NACA Lewis Research Center in 1951 as a researcher in the internal fluid dynamics of gas turbine engines, large solid rockets, and noise control of civil transport engines. In 1971 he moved to NASA Headquarters, where he held a variety of research management posts in the Office of Aeronautics and Space Technology (OAST) before being named Associate Administrator for Aeronautics and Space Technology in 1976. While at NASA, Mr. Kramer received medals for Exceptional Service, Outstanding Leadership, and Distinguished Service.

JOHN H. McELROY is presently Dean of Engineering at the University of Texas at Arlington. He was formerly Vice-President for Technology of Hughes Communications, Inc., a subsidiary of the Hughes Aircraft Company. Dr. McElroy joined Hughes in 1985 as Director of Special Projects in the Space and Communications Group, after serving as an assistant administrator of the National Oceanic and Atmospheric Administration (NOAA), where he directed the nation's program in civil operational Earth observations from space. From 1966 to 1982, he served with the National Aeronautics and Space Administration (NASA), where his last position was Deputy Director, Goddard Space Flight Center. He previously performed laser research at the Quantum Electronics Research Laboratory of the University of Texas at Austin (1963-66) and taught electronics in the U.S. Army's air defense guided missile program (1957-63). Dr. McElroy is a Fellow of the Institute of Electrical and

Electronics Engineers, the American Institute of Aeronautics and Astronautics, the Washington Academy of Sciences, and a member of the Board of Directors of the American Astronautical Society.

GEORGE B. MERRICK is Vice President, Engineering and Mission Analysis, for Rockwell International's North American Space Operations. He is responsible for the technical aspects of the corporation's manned space transportation programs, unmanned satellite programs, propulsion systems, and advanced technology programs. Mr. Merrick joined what was then the Space Division in 1966, serving as Director, Apollo System Engineering, and Chief Apollo Program Engineer. He subsequently became Vice President in charge of the company's efforts for the cislunar and lunar scientific missions, the Skylab spacecraft, and the Apollo-Soyuz Test Project. He was appointed Vice President and Program Manager of the Space Shuttle Orbiter Project in 1976, and became President of the Space Division in 1976. He was named to his present position in 1980. Since joining Rockwell in 1949, Mr. Merrick has held key engineering posts on projects which included (besides those already mentioned) the X-15, the F-100 supersonic fighter, and the XB-70 (a triplesonic delta-winged bomber). He is a Fellow of both the American Institute of Aeronautics and Astronautics and the American Astronomical Society.

JOHN E. NAUGLE, consultant, recently retired as director of the Leasecraft program at Fairchild Industries. Prior to that he had been, from 1975 to 1981, NASA Associate Administrator and Chief Scientist. He had a long and distinguished career at NASA, beginning at the Goddard Space Flight Center in 1959 and continuing at NASA Headquarters starting in 1960 where he was Director of the Physics and Astronomy Program and later Associate Administrator of the Office of Space Science from 1967 through 1974. Holding a Ph.D. in physics from the University of Minnesota, he is a member of the American Physical Society, the American Institute of Aeronautics and Astronautics, and the American Geophysical Union. His many awards include the NASA Distinguished Service Medal for his leadership of the Space Science and Applications Program (1969); again for his direction of the Viking Program (1977); the Career Civil Service Award for Sustained Excellence (1977); the NASA Distinguished Public Service Medal (1982); and the Outstanding Achievement Award from the University of Minnesota (1976).

DONALD O. PEDERSON is a Professor of Electrical Engineering and Computer Sciences at the University of California, Berkeley. He received his Ph.D. from Stanford University in 1951. Before coming to Berkeley in 1955, he engaged in research at Stanford and at Bell Telephone Laboratories. His research and teaching interests are in microelectronics, especially in the computer-aided design aspects. At Berkeley, Dr. Pederson has been the Director of the Electronics Research Laboratory and Chairman of the Department of Electrical Engineering and Computer Sciences. He is a former Guggenheim Fellow; he is also a Fellow of the Institute of Electrical and Electronic Engineers, and has received its Education Medal, a Centennial Medal, and an Outstanding Development Award from the Solid-State Circuit Council. Dr. Pederson is a member of the National Academy of Engineering and the National Academy of Sciences.

JOSEPH F. SHEA is Senior Vice President for Engineering at the Raytheon Company, where he is responsible for technology and advanced planning throughout the company. He joined Raytheon in 1968 as Vice President and General Manager of the Equipment Division, and was later Group Executive before assuming his present position in 1981. Dr. Shea was with NASA from 1963 to 1968, serving first as Deputy Director of Manned Space Flight for Systems Engineering and later as manager of the Apollo Spacecraft Program at Houston. At General Motors from 1959 to 1962, he was Director of Advanced Development and Manager of Ballistic Missile Guidance Development. He began his careeer as a research mathematician at Bell Telephone Laboratories. Dr. Shea is a member of the National Academy of Engineering, and has participated in many studies for the National Research Council and the Department of Defense.

MORRIS A. STEINBERG is an aerospace engineering consultant and Adjunct Professor of Materials Science and Engineering at the University of California at Los Angeles. Dr. Steinberg was formerly Vice President for Science at the Lockheed Corporation. Prior to holding that post he served in a number of key technical managerial capacities within Lockheed, including: Director of Technology (1974-1983), Deputy Chief Scientist (1965-1974), and Director of the Materials Sciences Laboratory at the Lockheed Missiles and Space Company (1958-1965), which he established.

Dr. Steinberg is a Fellow of the American Institute of Chemists, the American Society for Metals, the American Association for the Advancement of Science, the American Institute of Aeronautics and Astronautics, the Institute for Advancement of Engineering, and is a member of the National Academy of Engineering. He has served on numerous national boards and committees of the Department of Defense, the National Research Council, and the Department of Commerce. Dr. Steinberg obtained his undergraduate and graduate degrees in Metallurgy from the Massachusetts Institute of Technology.

A. THOMAS YOUNG is a Senior Vice President of the Martin Marietta Corporation and President of its Electronic and Missiles Group, headquartered in Orlando, Florida. Mr. Young joined Martin Marietta in 1982, after 21 years with NASA, and has served in key executive positions at the corporation's headquarters in Bethesda, Maryland, and at its Baltimore and Orlando operations. While at NASA, he served in various capacities including Director of the Goddard Space Flight Center and Mission Director for the Viking Mars landing program. Mr. Young obtained undergraduate degrees in aeronautical and mechanical engineering from the University of Virginia and a master's degree in management from MIT, which he attended as a Sloan Fellow.

LAURENCE R. YOUNG is a Professor of Aeronautics and Astronautics at the Massachusetts Institute of Technology. His area of expertise is biomedical engineering, with a special emphasis on space medicine and biology. Dr. Young was a Principal Investigator on vestibular experiments aboard Spacelabs -1, -4, and D-1, and is the inventor of an eye movement monitor used in vestibular and other physiological research. He has been on the faculty of MIT since 1962, having received his Sc.D. there in the same year. Dr. Young is a member of the National Academy of Engineering, the Aerospace Medicine Association, and the American Institute of Aeronautics and Astronautics. He is a charter member and past president of the Biomedical Engineering Society, and a Fellow of the Institute of Electrical and Electronics Engineers. He has served on several national boards and committees, including the Air Force Scientific Advisory Board and the NRC Space Science Board's Committee on Space Medicine and Biology.

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Acronyms and Abbreviations

ACTS	Advanced Communications Technology Satellite
AF	Air Force
ALV	Autonomous Land Vehicle
arc sec	1/60 of an arc minute, arc minute = 1/60 degree
ASAT	antisatellite
atm	atmosphere (standard unit of measurement)
AU	astronomical unit
AWACS	Airborne Warning and Communications System
AXAF	Advanced X-ray Astrophysics Facility
bit	binary digit (single, basic unit of information)
byte	a string of binary digits, usually eight, operated on as a basic unit by a digital computer
CELSS	Closed Ecological Life Support System
CO_2	carbon dioxide
COSMIC	Coherent System of Modular Imaging Collectors

CSI	control structure interaction
CSTI	Civil Space Technology Initiative (NASA)
CTE	coefficient of thermal expansion
DARPA	Defense Advanced Research Projects Agency
DMSP	Defense Meteorological Satellite Program
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EOS	Earth Observing System
eV	electron volt (electric energy)
EVA	extravehicular activity
g; 1-g	gravity; equivalent to one times the acceleration of gravity
GEO	geosynchronous orbit
GNS	guidance and navigation system
GRO	Gamma Ray Observatory
HIRIS	High-Resolution Imaging Spectrometer
HST	Hubble Space Telescope
ICBM	Intercontinental Ballistic Missile
IMU	inertial measurement unit
IRAS	Infrared Astronomical Satellite
IR	infrared
Isp	specific impulse
JSC	Johnson Space Center
K	Kelvin
kg	kilogram
km	kilometer
kW	kilowatt
lbs	pounds

LDR	Large Deployable Reflector
LEO	low Earth orbit
LM	Lunar Module
LOX	liquid oxygen
LOX-H_2	liquid oxygen-hydrogen
m	meter
M^2	square meter
Mb/sec	megabits per second
MB	megabytes
mm	millimeter
MSFC	Marshall Space Flight Center
MSR	Mars Sample Return mission
MWe	megawatts of electric power
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NASTRAN	NASA Structural Analysis
NAVSTAR	navigation system using time and ranging
NCOS	National Commission on Space
NDT	nondestructive testing
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRDS	Nuclear Rocket Development Station
NROSS	Naval Research Ocean Satellite System
OAST	NASA Office of Aeronautics and Space Technology
OSF	NASA Office of Space Flight
OSS	NASA Office of Space Station

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OSSA	NASA Office of Space Science and Applications
OSTDS	NASA Office of Space Tracking and Data Systems
OTV	orbital transfer vehicle
PM	powder metal
psi	pounds per square inch
R&D	research and development
RF	radio frequency
ROVER/NERVA	direct nuclear propulsion development program, 1955-1970
RST	rapid solidification technologies
R&T	research and technology
RTG	Radioisotope Thermoelectric Generator
SAFE	Solar Array Flight Experiment
SAM	Active Microwave Sensors
SAR	synthetic aperture radar
SDI, SDIO	Strategic Defense Initiative (Office)
SIRTF	Space Infrared Telescope Facility
SISP	Surface Imaging and Sounding Package
SLBM	Submarine-Launched Ballistic Missile
SSME	Space Shuttle Main Engine
STS	Space Transportation System
TAU	thousand astronomical units
TOPEX	Tropical Ocean Topography Experiment
TPS	thermal protection system
UARS	Upper Atmosphere Research Satellite
UV	ultraviolet
VHSIC	very high speed integrated circuit

Appendixes

Appendix A
Space Research and Technology—Economic Considerations

Wolfgang H. Demisch

Aerospace is the core stronghold of the U.S. manufacturing industry. Although smaller in size than either automotive or electronics, the industry far exceeds both in its contribution to the U.S. balance of trade. Exports generated over 18 percent of its 1986 sales of $104 billion, representing about 250,000 aerospace jobs. The aerospace trade balance was in surplus by $10.9 billion in 1986, exceeding $10 billion for the eighth consecutive year.

U.S. leadership in this sector was bought at heavy cost, during World War II and the subsequent Cold War, by sustained, balanced investment in the necessary research experiments and facilities as well as with appropriate production plants and operating support. It is a measure of the worth and the quality of these investments that the United States continues to lead in the world aerospace market despite a long period of underfunding, particularly for the basic and applied research categories.

Spending on aerospace basic and applied research fell from 21 percent in 1962 to 11.6 percent by 1977, and has only begun to recover in recent years.[1] This decline was in the context of a steady overall decrease in the research and development to sales ratio of the U.S. aerospace industry, from 25.3 percent in 1962 to a recent low of 17.3 percent in 1983, with again some recovery since then.

The slower technical progress resulting from this reduced R&D commitment has had predictable consequences because the United States is not the sole aerospace supplier in the world. Indeed, the world market is more competitive than the steady succession of U.S. aerospace trade surpluses would indicate. In Japan, aerospace is explicitly recognized as a strategic industry for the twenty-first century and as an essential driver for the modernization of industrial processes and capabilities by the Ministry for International Trade and Industry (MITI). In Europe, a very aggressive and well-financed push forward on all fronts of aerospace technology is also under way, including an estimated $15 billion commitment to date solely for the Airbus Industrie jetliner consortium.

These competitors have gained much ground over the past 15 years. For example, Airbus is now second in civil transport, having captured 23 percent of the 1986 jetliner orders. More generally, the U.S. aerospace trade balance, which had perennially been in surplus by a 10 to 1 ratio or better (and still was so late as 1978), is now running only about 2 to 1 in our favor. Imports in 1986 totaled $8.1 billion, equivalent to a job cost of well over 100,000. Even more pointedly, U.S. leadership has been lost in entire aerospace business sectors. For example, since 1980, the trade balance has turned increasingly negative in the general aviation category, the easiest and cheapest segment for a competitor to enter, and the area most neglected in terms of research. The trade balance in general aviation is now tilted 4 to 1 in favor of imports. Because of the stagnant technology base, the U.S. general and commuter aviation industry has been unable to fend off foreign competitors, who exploited their lower labor and capital costs to produce technically competitive products at a better price. This is a depressing outcome given that almost the entirety of this market is in the United States.

Although these cautionary examples apply primarily in aeronautics, they are of special relevance in space. Space, along with information technology and the life sciences, represents one of the great frontiers of our day, with perhaps the largest long-term potential of these three. As in aeronautics, the nation looks to NASA to provide the technology base to preserve U.S. leadership in this arena, a leadership that is likewise under attack and indeed which may be in doubt given the massive Soviet effort and their demonstrated launch capacity as well as the ambitious European program and the carefully focused Japanese push.

The subject of the accompanying report is the amount of emphasis that should be put on space technology, i.e., basic and applied research on space launch techniques and space vehicles. The experience in aeronautics over the past 25 years has been for R&D to make up between 17 and 25 percent of sales, with research, both basic and applied, varying from 11 to 24 percent of that, or between 2 and 6 percent, averaging about 3 percent, of industry sales.

Given the evident decay of the U.S. lead made manifest by the trade balance erosion, it is apparent that this past level of effort has fallen short of what was required to maintain our competitive position.

The shortfall appears much more pronounced in the area of space. The current level of effort for space research and technology is running at about 1 percent of the $20 billion space-related revenues, well below the demonstrably inadequate aerospace industry norms. Space is a much younger field than aeronautics and consequently at a relatively early stage of development, with a correspondingly greater ability to absorb usefully the technology investment. In addition, space is the most rapidly growing market in aerospace, having quadrupled in the last decade for a 16 percent revenue growth rate versus 11.5 percent for the entire aerospace industry. This more rapid expansion suggests comparably greater opportunity for returns on the resources invested in the underlying R&T. Under current budgets, those opportunities will not be seized by the United States. Moreover, although some increases are now planned under the Civil Space Technology Initiative, even the proposed enhanced program appears insufficient to fulfill the national mandate, articulated by the Space Act, for U.S. primacy in this arena.

The bolder plan proposed by the National Commission on Space, for a tripling of the NASA space R&T effort, appears to be the minimum step needed to safeguard U.S. competitiveness in this area. However, based on the record of the aeronautics industry, even that level of expenditures (6 percent of NASA's budget or about 2 to 3 percent of the total space revenue base) is unlikely to be sufficient to allow U.S. leadership to be broadened, unless it is carefully integrated with comparable work done on a similar scale by the military and by private industry. Nor is an enhanced

research program alone adequate to assure U.S. preeminence; adequate development and operations programs will be required. Basic research, however, is obviously the foundation upon which the structure of the space program must rest.

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1. Aerospace Industries Association (AIA). "Aerospace Facts and Figures." Washington, D.C.: AIA, 1986.

Appendix B
List of Participants

NASA REPRESENTATIVES

NASA Headquarters Liaison Representatives

Frederick P. Povinelli, Assistant Associate Administrator for Management, OAST
Leonard A. Harris, Director for Space, OAST

NASA Headquarters

Raymond Colladay, Associate Administrator, OAST
John L. Anderson, Program Manager for Large Space Systems Technology, OAST
Darrell Branscome, Special Assistant to the Associate Administrator for Space Flight
Harold L. Compton, Assistant Director for Space, OAST
Edward A. Gabris, Director, Propulsion, Power, and Energy Division, OAST
David A. Gilman, Astrophysics Division, OSSA
Michael A. Greenfield, Program Manager for Materials Structures, OAST
Wayne R. Hudson, Assistant Director for Space, OAST

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Dudley G. McConnell, Assistant Associate Administrator, OSSA
Sally Ride, Special Assistant to the Administrator for Strategic Planning
Carol Roberts, Acting Deputy Director for Information Sciences and Human Factors Division, OAST
James M. Romero, Assistant Director for Space, OAST
Robert Rosen, Deputy Associate Administrator, OAST
Stan Sadin, Assistant Director for Program Development, OAST

Ames Research Center

William F. Ballhaus, Director
Alan B. Chambers, Director for Space Research
Palmer Dyal, Assistant Director for Space Research
Henry Lum, Chief, Information Sciences Office
Douglas A. O'Handley, Chief of Advanced Technology, Space Station Planning Office
Thomas Snyder, Director of Aerospace Systems Directorate

Goddard Space Flight Center

Henry Plotkin, Assistant Director for Development Projects

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Richard Miller, Manager, Information System Program Office
Donna Pivirotto, Manager, Robotics Division
William J. Weber, Manager of Technology Program

Langley Research Center

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Robert R. Nunamaker, Director for Space
Gerald Walberg, Technology Study Manager, National Security Defense Directive Space Transportation Study

Lewis Research Center

Stuart J. Fordyce, Director of Aerospace Technology

Marshall Space Flight Center

S. F. Morea, Director, Research and Technology Office

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Aerojet Propulsion Research Institute

William H. Heiser, Vice-President and Director
John Halligan, Research Manager, Mission/Payload Analysis
Dave L. Kors, Research Manager, Propulsion Systems

The Aerospace Corporation

Robert A. Davis, Chairman, American Institute of Aeronautics and Astronautics Study, Projections of Space Systems Opportunities

EFFORT, Inc.

Owen Garriott, Aerospace Consultant and President

Rockwell International Corporation

George Hallinan, Program Director, Rocketdyne Division

NATIONAL RESEARCH COUNCIL

Space Science Board

Thomas Donahue, Chairman

UNIVERSITIES

Massachusetts Institute of Technology

James W. Mar, Hunsaker Professor of Aerospace Education

Stanford University Medical Center

William Decampli, Department of Surgery

Worcester Polytechnic Institute

Peter E. Green, Department of Electrical Engineering

U.S. AIR FORCE

David Glasgow, Project Forecast II
Joseph Janni, Senior Adviser, Air Force Space Technology Center

Appendix C
Responders to Aerospace Industry Survey

BALL AEROSPACE SYSTEMS DIVISION, L. R. Greenwood, Vice-President, Strategic Operations
BOEING AEROSPACE COMPANY, Donald B. Jacobs, Vice President, Space Systems Division
BOEING AEROSPACE OPERATIONS, Edward J. Renouard, President
COMPUTER SCIENCES CORPORATION, William Schneider, Vice-President, Development, System Sciences Division
COMSAT LABORATORIES, John V. Evans, Vice-President, Research and Development and Director of COMSAT Laboratories
EAGLE ENGINEERING, INC., Bass Redd, Chief Executive Officer and President
FAIRCHILD SPACE COMPANY, Martin N. Titland, President
GENERAL DYNAMICS, A. M. Lovelace, Corporate Vice-President and General Manager, Space Systems Division
GENERAL ELECTRIC COMPANY, Richard W. Hesselbacher, Manager, Advanced Development and Information Systems, Space Systems Division
GRUMMAN CORPORATION, Willard R. Bischoff, Vice-Chairman, Technology

HONEYWELL, B. Craig Tierney, Director Honeywell Power Sources Center
HUGHES AIRCRAFT COMPANY, R. M. Talley, President, Santa Barbara Research Center
HUGHES AIRCRAFT COMPANY, David Brown, Director, Technical Operations, Space and Communications Group
IIT RESEARCH INSTITUTE, Sidney I. Firstman, Director, New Business Development
ILC DOVER, INC., Homer D. Reihm, President and General Manager
THE MARQUARDT COMPANY, Mary Hodgson, Contract Administrator
MARTIN MARIETTA CORPORATION, Maynard L. Sikes, Director of Research
MCC, John T. Pinkston, Vice-President and Chief Scientist
McDONNELL DOUGLAS ASTRONAUTICS COMPANY, John F. Yardley, President
MORTON THIOKOL, INC., E. G. Dorsey, Jr., Vice-President and General Manager, Space Division
MOTOROLA, INC., Durrell W. Hillis, Vice-President and General Manager, Strategic Electronics Division
NOVACOM, Donald K. Dement
OAO CORPORATION, Robert Lambeck, Engineering Technology
RCA, R. A. Stampfl, Manager, Advanced Missions
SATELLITE SYSTEMS ENGINEERING, INC., Wilbur L. Pritchard
THE SINGER COMPANY, William D. Turner, Group Vice-President, Training Systems
SPECTROLAB, INC., Hans G. Dill, Vice President, Advanced Programs and David R. Lillington, Assistant Manager, Advanced Programs
HR TEXTRON INC., Louis A. Drazin, Vice President
TRW SPACE & TECHNOLOGY GROUP, R. F. Brodsky
TRW SPACE & TECHNOLOGY GROUP, Edsel D. Dunford, Vice President and General Manager
U.S. DEPARTMENT OF COMMERCE, William P. Bishop, Deputy Assistant Administrator for Satellites, National Environmental Satellite, Data, and Information Service, National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF THE INTERIOR, John D. Tabb, Chief, Division of Engineering, Bureau of Land Management

WESTERN UNION TELEGRAPH COMPANY, F. W. Ziegler, Executive Consultant

WESTINGHOUSE ELECTRIC CORPORATION, J. H. Meacham, Manager, Space and Technology Divisions Program Development

NATIONAL RESEARCH COUNCIL
COMMISSION ON ENGINEERING AND TECHNICAL SYSTEMS
2101 Constitution Avenue Washington D.C. 20418

AERONAUTICS AND SPACE
ENGINEERING BOARD

September 8, 1986

Dear :

The Aeronautics and Space Engineering Board is undertaking a study for the National Aeronautics and Space Administration to determine needs for basic research in space technologies which may be required over the next 30 years.

NASA's Office of Aeronautics and Space Technology (OAST) has the task of providing a broad technology base for the future as well as responding to current technology needs. Traditionally, the development of new concepts, new materials, designs, and engineering techniques for aeronautics has been accomplished in cooperation with the aircraft industry and with American universities. On the other hand, NASA, as the primary user of space flight, has been its own principal customer for new space technologies. In October of 1985, at a workshop at Williamsburg, Virginia, OAST initiated a long-term outreach program to focus on the needs of industry and universities for in-space experiments and to promote a national "user constituency" for space research and engineering. As a continuation of this outreach program, we are seeking the views of major space contractors and subcontractors. This input will be used in helping OAST shape its future technology development program.

It would be helpful to us in undertaking the study of advanced space technology needs to learn your views regarding the following:

1. Need. From your view, what are the greatest needs for technological advances or breakthroughs in space technology areas? This might include new capacities, enhanced performance or reduced costs.

2. Opportunity. Can you see technical areas that show promise of offering new techniques to accomplish tasks being performed another way? Can you perceive what might be effective areas to investigate to improve the performance or efficiency of space systems?

The National Research Council is the principal operating agency of the National Academy of Sciences and the National Academy of Engineering to serve government and other organizations.

3. NASA's Role. In what areas would you like to see NASA make concentrated technology development efforts? In what other areas would you value a sustained NASA development program? What past NASA programs have been of value to you?

We hope you will take the time to respond to the above questions. Please do not limit your response to these questions if you have additional comments or suggestions. We would like to receive your reply by October 1, 1986. Should you have any questions or wish to discuss this matter further, please call JoAnn Clayton, Study Director, at 202/334-2855. Your reply should be mailed to:

J. Clayton
Aeronautics and Space Engineering Board
National Research Council, JH 413
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

We will greatly appreciate your assistance and hope to share with you the results of this survey and of the committee's deliberations over the next months.

Sincerely,

Joseph F. Shea
Chairman

Appendix D
Responders to University Survey

AUBURN UNIVERSITY, M. Dayne Aldridge, Assistant Dean for Research, College of Engineering

CALIFORNIA INSTITUTE OF TECHNOLOGY, Edward E. Zukoski, Professor of Jet Propulsion and Mechanical Engineering, Daniel and Florence Guggenheim Jet Propulsion Center and Karman Laboratory of Fluid Mechanics and Jet Propulsion

CALIFORNIA POLYTECHNIC STATE UNIVERSITY, James G. Harris, Head, Department of Electronic and Electrical Engineering

CLARKSON UNIVERSITY, William R. Wilcox, Director, Center for Advanced Materials Processing and Center for the Development of Commercial Crystal Growth in Space

COLORADO STATE UNIVERSITY, Raymond S. Robinson, Associate Professor, Department of Physics

COLORADO STATE UNIVERSITY, Paul J. Wilbur, Professor, Department of Mechanical Engineering

CORNELL UNIVERSITY, Simon H. Bauer, Professor of Physical Chemistry, Baker Laboratory

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY, Rene H. Miller, H. N. Slater Professor of Flight Transportation, Department of Aeronautics and Astronautics
MICHIGAN TECHNOLOGICAL UNIVERSITY, A. Hellawell, Professor, Department of Metallurgical Engineering, College of Engineering
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NORTH CAROLINA STATE UNIVERSITY, Klaus J. Bachmann, Professor of Chemistry and Materials Science and Engineering, School of Physical and Mathematical Sciences
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PURDUE UNIVERSITY, P. E. Liley, Professor, Mechanical Engineering
PURDUE UNIVERSITY, Robert E. Skelton, Professor, School of Aeronautics and Astronautics
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RENSSELAER POLYTECHNIC INSTITUTE, Robert G. Loewy, Institute Professor, The Margaret and Erik Jonsson Engineering Center
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STANFORD UNIVERSITY, C. Chapin Cutler, Emeritus Professor, Applied Physics, Ginzton Laboratory

STANFORD UNIVERSITY, Joseph Oliger, Associate Professor, Department of Computer Science
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UNIVERSITY OF CALIFORNIA, BERKELEY, A. K. Oppenheim, Professor, Mechanical Engineering, College of Engineering
UNIVERSITY OF CALIFORNIA, LOS ANGELES, Paul J. Coleman, Jr., Professor of Space Physics and Geophysics, Institute of Geophysics and Planetary Physics
UNIVERSITY OF CALIFORNIA, LOS ANGELES, T. H. K. Frederking, Professor, School of Engineering and Applied Science
UNIVERSITY OF CALIFORNIA, SAN DIEGO, A. L. Berlad, Professor, Energy Center
UNIVERSITY OF CALIFORNIA, SAN DIEGO, S. S. Penner, Professor of Engineering Physics and Director, Center for Energy and Combustion Research
UNIVERSITY OF COLORADO, BOULDER, G. Born, Colorado Center for Astrodynamics Research
UNIVERSITY OF COLORADO, BOULDER, George W. Morgenthaler, Chairman, Aerospace Engineering Sciences
UNIVERSITY OF COLORADO, BOULDER, A. Richard Seebass, Dean, College of Engineering and Applied Science
UNIVERSITY OF FLORIDA, Mark H. Clàrkson, Professor Emeritus, Department of Engineering Sciences, College of Engineering
UNIVERSITY OF HOUSTON, Alvin F. Hildebrandt, Director, Energy Laboratory
UNIVERSITY OF IDAHO, Gary K. Maki, Buchanan Engineering Laboratory, College of Engineering
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UNIVERSITY OF MARYLAND, J. Silverman, Professor, Department of Chemical and Nuclear Engineering
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UNIVERSITY OF TEXAS AT AUSTIN, Victor Szebehely, Department of Aerospace Engineering and Engineering Mechanics

UNIVERSITY OF TEXAS AT AUSTIN, Delbert Tesar, Carol Cockrell Curran Chair in Engineering

UNIVERSITY OF UTAH, J. D. Andrade, Dean, College of Engineering

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UNIVERSITY OF WASHINGTON, Juris Vagners, Professor, Department of Aeronautics and Astronautics, College of Engineering

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YALE UNIVERSITY, Peter P. Wegener, Harold Hodgkinson Professor of Engineering and Applied Science, Center for Applied Mechanics

NATIONAL RESEARCH COUNCIL
COMMISSION ON ENGINEERING AND TECHNICAL SYSTEMS
2101 Constitution Avenue · Washington, D.C. 20418

AERONAUTICS AND SPACE
ENGINEERING BOARD

October 10, 1986

Dear :

The Aeronautics and Space Engineering Board is undertaking a study for the National Aeronautics and Space Administration to determine needs for basic research in space technologies which may be required over the next 30 years and to recommend a NASA research and technology program.

NASA's Office of Aeronautics and Space Technology (OAST) has the task of providing a broad technology base for the future as well as responding to current technology needs. Traditionally, the development of new concepts, new materials, designs, and engineering techniques for aeronautics has been accomplished in cooperation with the aircraft industry and with American universities. On the other hand, NASA, as the primary user of space flight, has been its own principal customer for new space technologies. In October of 1985, at a workshop at Williamsburg, Virginia, OAST initiated a long-term outreach program to focus on the needs of industry and universities for in-space experiments and to promote a national "user constituency" for space research and engineering. As a continuation of this outreach program, we are seeking the views of members of the university community engaged in research relevant to the space program. This input will be used in helping OAST shape its future technology development program.

It would be helpful to us in undertaking the study of advanced space technology needs to learn your views regarding the following:

1. Need. From your view, what are the greatest needs for research and for technological advances or breakthroughs in space technology areas? This might include new capacities, enhanced performance, or reduced costs.

2. Opportunity. Can you see technical areas that show promise of offering new techniques to accomplish tasks being performed another way? Can you perceive what might be effective areas to investigate to improve the performance or efficiency of space systems?

The National Research Council is the principal operating agency of the National Academy of Sciences and the National Academy of Engineering to serve government and other organizations.

3. NASA's Role. In what areas would you like to see NASA support strong, concentrated technology development efforts? In what other areas do you believe a sustained research and development effort should be maintained? What past NASA programs do you believe have been of greatest value?

We hope you will take the time to respond to the above questions. Please do not limit your response to these questions if you have additional comments or suggestions. We would like to receive your reply by October 31, 1986, if possible. Should you have any questions or wish to discuss this matter further, please call JoAnn Clayton, Study Director, at 202/334-2855. Your reply should be mailed to:

J. Clayton
Aeronautics and Space Engineering Board
National Research Council, JH 413
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

We will greatly appreciate your assistance and hope to share with you the results of this survey and of the committee's deliberations over the next months.

Sincerely,

Joseph F. Shea

Joseph F. Shea
Chairman

National Academy Press

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